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A Study on Site Identification for Utility Scale Solar PV Energy Generation in Nepal

by

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A THESIS

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DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled **"A Study on Site Identification for Utility Scale Solar Energy Generation in Nepal"** submitted by Bidit Devkota, in partial fulfillment of the requirements for the degree of Master of Science in Renewable Energy Engineering.

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ABSTRACT

Site selection for solar PV based energy generation is a complex decision making process as several parameters like Irradiance, slope, electrical grid, distance to road/river etc., need to be optimized. In this study, an assessment on site selection for utility scale solar PV energy generation in Nepal was conducted based upon set decision variables and constraints. GIS based MCDM methodology was employed in this study to determine the weightage of identified criteria through Analytical Hierarchy Process (AHP). The methodology was employed for the study as it may reduce the cost associated with extensive site survey and hence widely used for policy formulation and decision making. Spatial analysis was conducted to output site suitability map in a scale of 1 to 5, 1 indicating areas with "Least Suitable" while 5 indicating areas "Most Suitable" to PV plant construction. The study identified parcels of land coverage of about 22.46 percent which was "Most Suitable" for construction of Solar PV plant if restriction criteria is not considered and 10.80 percent of land as "Most Suitable" for construction of PV plant if restriction criteria is taken into consideration. Likewise, an optimum number of 1,376 identified sites with area coverage of 51.235 sq. km, with solar insolation potential of 251.11 GWhr/day have been identified as potential site for solar PV plant construction. Although the study is based on Nepalese data. it may be proved equally valuable for academia and industry working under similar context.

Thus, a GIS based MCDM method can be beneficial tool for policy and decision makers, academics to focus with research at greater precision on those area having higher significance.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEPC	Alternative Energy Promotion Centre
AHP	Analytic Hierarchy Process
AHP	Analytical Hierarchy Process
BOS	Balance Of System
CP	Compromise Programming
CR	Consistency Ratio
CRS	Coordinate Reference System
DEM	Digital Elevation Model
DSS	Decision Support System
ELECTRE	Elimination and Choice Translating Reality
EPSG	European Petroleum Survey Group
FLOWA	Fuzzy Logic Ordered Weight Averaging
FMF	Fuzzy Membership Functions
GIS	Geographic Information System
IEA	International Energy Agency
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MCE	Multi-Criteria Evaluation
NREL	National Renewable Energy Laboratory
NTE	Nominal Terrestrial Environment
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PV	Photovoltaics
RDBMS	Relational Data Base Management System
RI	Random Index

SI	Suitability Index
SWIR	Short-Wave Infrared
TIR	Thermal Infrared
TOPSIS	Technique for Ordered Preference by Similarity to Ideal Solution
UTC	Universal Transverse Mercator
VNIR	Visible and Near Infrared
WGS	World Geodetic Standard
WPM	Weighted Product Model
WSM	Weighted Sum Model
XS	Multispectral bands.

CHAPTER ONE: INTRODUCTION

1.1 Background

Solar energy replacing conventional non-renewable energy is being widely implemented around the world. Of the total new power generation capacity installed worldwide, it was estimated that in 2018 about 34 % was derived from photovoltaic electricity generation (Jäger-Waldau, 2019). Currently, one of the most challenging problems is to improve the efficiency, capacity and sustainability of producing solar energy taking into account Geological, Technological, and Socio-Economical factors. Before carrying out large scale construction of solar farm, assessing the site location significantly benefit the life cycle power production performance of project. The aim of this study is to conduct a site selection analysis for utility scale solar farming using Geographical Information Systems (GIS). The possibility of carrying out the analysis, management, storage and visualization of all geospatial information can be done perfectly by the combination of GIS with technical decision support (Malczewski, 1999)

Recently, positive investment climate, strong property rights, and low tax regimes, with established participation in the power sector from private parties has started taking place and Government of Nepal has started providing incentives to more solar energy applications in the country in the form of tax and investment subsidy. However, without an accurate database and knowledge of most appropriate locations of renewable energy applications in the country, investment in renewable energy will not be efficient and profitable in the long run. This can be achieved by producing solar radiation and land suitability maps for Nepal. For the models, planning and advancement of solar energy devices/applications and development of solar plants accurate data base of solar radiation at particular places and selected sites are necessary. (Adhikari, et al., 2013)

For a micro installation of a solar farm (residential PV panels, flat plate solar collector / concentrating type solar collector) suitable for use limited within a single family, study can be carried out using empirical methods of on-site assessment. However, with scaling of power production capacity, problem associated with topography (landscape, terrain, distance from habitation, distance from roads and distance from grid) play key factor. (Gastli & Charabi, 2010) describes that the variation in slope/aspect, elevation, and shadows of topographic features affect the solar radiation's amount received at different locations. This spatial variability also changes with time, day and year. Therefore, GIS tools are required and essential for such analysis.

1.2 Problem Statement

Site selection is a spatial problem that requires inputs of large volume of technological, topographical, environmental, governmental incentives and social data (Uyan, 2013). Modern progressions in GIS have developed procedures to identify, rank and map sites that are suitable or unsuitable for a specific purpose. A site-selection procedure based on GIS can be potentially useful to recognize suitable areas through the identification and mapping of location where the construction of plant is guaranteed to produce measurable output in energy production at an optimum cost and benefit.

Despite its immense application, it has not been widely used in the study of site identification at the optimum location. Whereas, such methodology may be proved instrumental in developing countries like Nepal where resources constraints in such studies dominantly prevails.

1.3 Rationale

Identifying optimal sites for solar power development helps policy leaders/formulators and other stakeholders by providing the detailed information of restricted area which is difficult to access physically. The advantages can be summarized below.

1) Optimization of Electrical Grid/Transmission line Planning
2) Development of master plan for multi-year power generation program
3) Screening of protected and sensitive areas
4) Assurance of return to private sector investment.

1.4 Objectives

1.4.1 Main Objective

- To identify Optimal Site for Utility Scale Solar Energy Generation in Nepal

1.4.2 Specific Objectives

- To study irradiance map for the full extent of Nepal utilizing data from SOLARGIS, USGS/SRTM, ICIMOD, DoR, GoN.
- To identify various criteria, constraints and standards that are essential for site selection based upon previous research and introduce new criteria that deem important and critical from the viewpoint of Nepal.
- To assess specific location, area coverage and solar PV potential of multiple sites within Nepal for utility-scale PV plant construction.

1.5 Scope and Limitation

In this study, the spatial analysis for potential Solar PV energy generation sites was carried out for the entire region of Nepal. Since the region under consideration covers a large geographical area with wide variation in the selected criteria of GHI, temperature, slope, aspect, road network, transmission lines etc. the adopted scheme of classifying the entire region within 5 segments only may result in some clustering of large region into same category. Similarly, this project largely depends on the secondary GIS data obtained from multiple sources including data related to road network, electric grid network, electric substation and PowerStation, hydrographical data, landuse/landcover data which are subject to change depending upon the time.

Chapter Two: Literature Review

This chapter provides a systematic review of Renewable energy, Solar PV technology, GIS system, MCDM technique along with the current energy scenario and future trends from Global and national perspective. The chapter takes into account past literature required for the selection of MCDM technique, site selection criteria as well as significance of the selected factors on the basis of which weighted overlay analysis is performed to fulfill the objective of the thesis.

2.1 Renewable Energy

Renewable energy technologies utilize Sun's energy (solar radiation, wind, flowing water, biomass, gravitational forces, tidal forces, and geothermal) and its direct/indirect effects on the earth as the resources from which energy is produced. These resources are found in diffused states and are not fully accessible and most of them are sporadic with distinct regional variabilities. (Kalogirou, 2004)

2.1.1 Solar Energy

The sun has an effective temperature of 5777 K with central interior regions variously estimated at 8×10^6 to 40×10^6 K having the density about 100 times that of water. Retained by its own gravitational forces, the sun emits radiated energy as a continuous fusion reactor (Duffie & Beckman, 2013).

According to the report of World Energy Council (WEC, 2013) the sun's energy is emitted at a rate of 3.8x1023 kW per second, and approximately 1.8×10^{14} kW is intercepted by the earth, which is a just a small fraction of it. Among that about 60% or 1.08×10^{14} reaches the surface of the earth, and only 0.1% of this energy could be converted at an efficiency of only 10%. Thus, it plays an appreciable role in reduction of carbon related emissions, ensuring a sustainable energy future which can be used for heating, cooling, lighting, electrical power, transportation.

Mode through which radiative solar energy reaches the Earth.

- **Total Solar Irradiance**: It is a measure of the solar power per unit area incident on the Earth's upper atmosphere measured upright to the incoming solar radiation.

- **Diffuse Horizontal Irradiance**: DHI or Diffuse Sky Radiation is the solar radiation received after the being scattered by the atmosphere. It is measured excluding radiation coming from the sun disk on a horizontal surface with radiation coming from all points in the sky.
- **Direct Normal Irradiance**: DNI or beam radiation excludes diffuse solar radiation and is measured at the surface of the Earth at a given location with a surface element perpendicular to the Sun.
- **Global Horizontal Irradiance**: it is the total irradiance from the sun measured on a horizontal surface on Earth. It is the sum of direct irradiance and diffuse horizontal irradiance.

2.2 Mechanism to Harness Energy from Sun

The two main types of solar energy technologies are photovoltaic and thermal collectors.

Photovoltaic collectors: PV collectors directly converts solar radiation into electricity, without conversion into any intermediate component. As a result, they are gaining increasing popularity in household/commercial building integration as well as for small and large-scale devices due to higher working efficiency.

These semiconductor devices convert the incoming solar radiation directly into electrical energy. Solar cells have found their use in a wide range of applications, from powering watches, calculators, charging batteries for boats and communications systems to medium-scale systems for power generation. PV collectors are the principal means of generating power for most of the satellites in majority of space programs. (Duffie & Beckman, 2013).

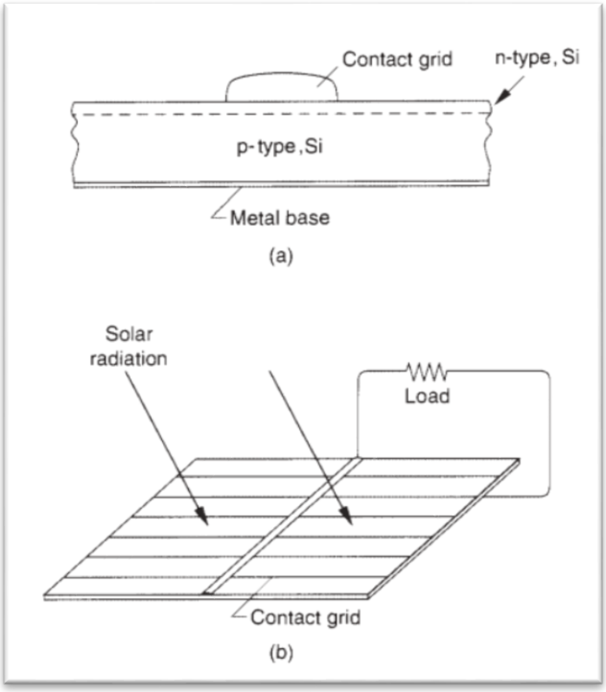

Figure 2.1: (a) Silicon Solar Cell's Cross section and (b) Top contact Schematic of solar cell (Duffie & Beckman, 2013)

Solar Thermal Collectors: Solar Thermal collectors are essentially form of heat exchangers that converts radiation energy to energy of the working mediums. It works by absorbing the incoming solar radiation, converts it into heat, and transfers the heat to usually air, water/oil flowing through the collector. The transferred solar energy collected by working medium is carried directly space conditioning equipment or to an energy storage medium.

Non-concentrating or stationary and Concentrating collector are the primary type of Solar Thermal Collector. A non-concentrating collector has equal area for absorbing solar radiation, whereas a concentrating solar collector usually has larger reflecting surfaces to capture the solar radiation to a smaller receiving space making them suitable for high-temperature applications. (Kalogirou, 2006).

2.3 Solar PV Energy scenario

2.3.1 Global Perspective

International Energy Agency (IEA) in its annual report World Energy Outlook, 2022 stated that Solar photovoltaics (PV) is the fastest-growing renewable energy technology, with global capacity increasing by 26% in 2022 to reach 1,300 GW. This growth was driven by strong demand in China, the United States, and Europe, as well as by falling costs. Solar PV is now the second-largest source of renewable electricity generation, after hydropower (Figure 2.2).

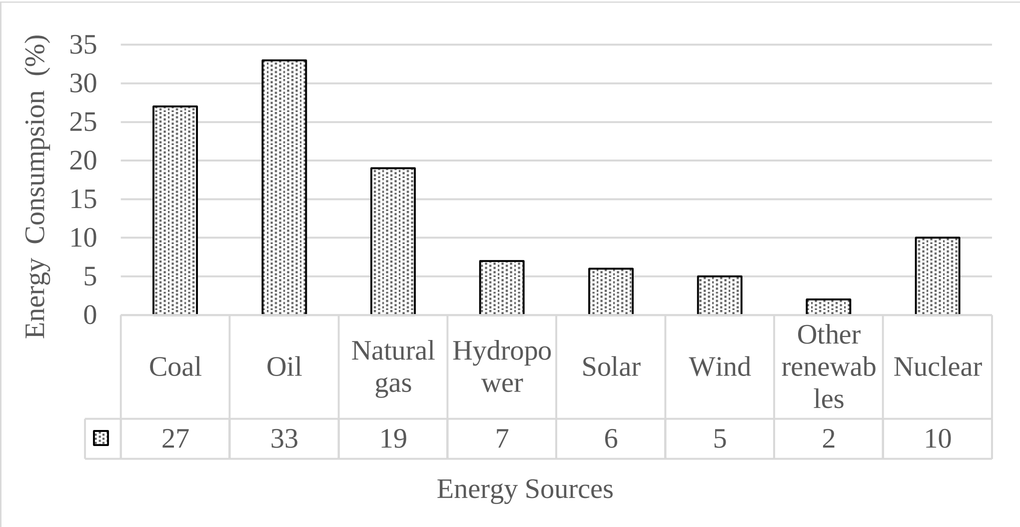

Figure 2.2: World Energy Consumption by Fuel Type for 2022 (IEA, 2022)

In 2022, solar PV accounted for 4.5% of global electricity generation. This share is expected to increase to 16% by 2030, as solar PV capacity reaches 2,800 GW. This growth will be driven by continued cost declines, as well as by policy support in many countries.

The International Energy Agency (IEA) projects that solar PV will be the largest source of renewable electricity generation by 2040. This is due to the technology's low cost, scalability, and environmental benefits. Solar PV is well-positioned to play a major role in the global energy transition, and it is expected to be a key contributor to meeting the goals of the Paris Agreement.

Table 2.1: Key Figures from World Energy Outlook, 2022

Particulars	Figures
Global solar PV capacity	1,300 GW (2022)
Projected solar PV capacity	2,800 GW (2030)
Share of global electricity generation from solar PV	4.5% (2022)
Projected share of global electricity generation from solar PV	16% (2030)

2.3.2 National Perspective

Nepal's energy system is largely dominated by traditional form of energy. In the national energy consumption spectrum, renewable fuel occupies 3%, commercial fuel occupies 32% and traditional form of energy occupies 65% (AEPC, 2022).

The sectoral utilization of energy shows that majority is utilized for residential purpose (63%) followed by a distant. second, the industrial sector at 18.3%.

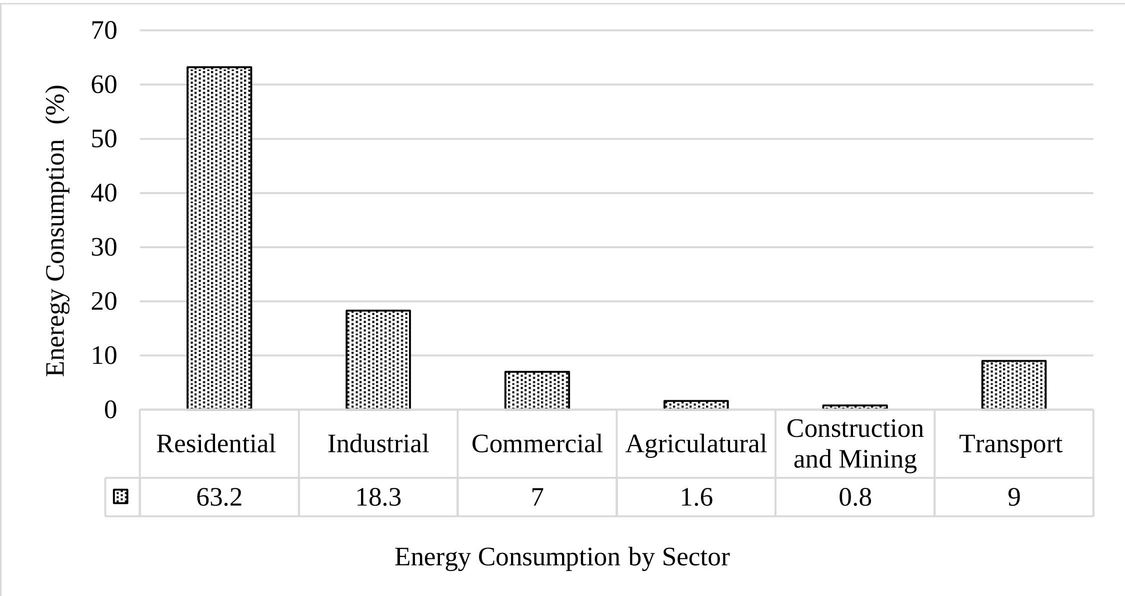

Figure 2.3: Sectoral Energy Consumption of 2021, (WECS, 2022)

2.4 GIS based Solar PV Research in Nepal

Research Initiation regarding large scale Solar PV in Nepal can be attributed to SWERA project, an UNEP initiative which mapped the solar potential throughout

Nepal (Schillings, et al., 2004). The research was further enhanced by SOLARGIS project which improved upon the methodology used for calculation of GHI, DNI, PVOut for the entire extent of Nepal. The estimated potential of Solar PV in Nepal is about 2100 MW owing to Nepal's average solar radiation varying between 3.6-6.2kWh/m2day with annual 300 days of sunshine (Shrestha, et al., 2022)

2.4.1 Utility scale Solar PV in Nepal

The history of Utility Scale Solar PV in Nepal started with JICA installed solar plant in Sundarighat at capacity of 600 KWp. According to Department of Energy Development (DoED), 5 solar PV projects totaling 24.18 MW of electricity have already been connected to national grid. 21 projects have already received construction license to produce about 133.56 MW and 44 projects have received survey license to produce 747.6 MW of electricity till July, 2023.

The development of solar energy in Nepal is still in its early stages, but the potential is great. With the right policies and investments, Nepal could become a major player in the global solar market

2.5 Institutional framework and policy for PV energy

The Ministry of Energy has declared the decade 2016- 2026 as the National Energy Crisis Reduction and Electricity Development Decade. Ministry of Finance has issued a Concept Paper on Elimination of Energy Emergency and Electricity Development Decade, 2015 to ensure Energy security within the next decade. (Pokharel, 2019)

The following institutional setup is responsible to oversee, monitor, empower, develop policy, rules and regulation for energy sector including Solar PV in Nepal

- Ministry of Energy, Water Resources and Irrigation
- National Water Resources Development Council
- National Planning Commission
- Water and Energy Commission Secretariat
- Nepal Electricity Authority
- Department of Electricity Development
- Electricity Tariff Fixation Commission
- Ministry of Forest and Environment
- Alternative Energy Promotion Centre

2.5.1 Government Plans, Policies & Programs governing PV energy generation

- Rural Energy Policy, 2006 AD
  - Providing necessary support for rural areas without grid power supply
  - Institutional setup and Rural Energy Fund provisions.
  - Rural renewable energy subsidy and mobilization of private sector, financial institution, NGOs and local organization
- Subsidy Policy for Renewable Energy, 2022 AD
  - financial arrangement/guidelines and subsidies.
  - Net metering program for urban solar energy.
  - Tax immunity/concession for import of solar energy systems, net metering equipment and LED lights.
- National Renewable Energy Framework, 2017 AD
  - Smart subsidy mechanism to quicken the conversion from subsidy centered model to a credit-focused model.
  - Improve accessibility to renewable energy.
- National Energy Efficiency Strategy, 2019 AD
  - To increase the improvement rate of energy efficiency in Nepal from 0.84% per annum during 2000 – 2015 AD to 1.68% per year during 2015-2030 AD. (WECS, 2022)

2.6 Geographic Information System (GIS)

GIS is a computer tool that integrates data, maps, and software to analyze geographic information. This powerful technology is used in many fields, such as urban planning, emergency response, and site selection. GIS visualization can simplify complex data and help decision-makers make better choices. (Hernandez, 2007)

2.6.1 Component of GIS

1. Data Models

GIS systems are primarily based on database, Relational data base management system (RDBMS) is the often applied approach for storing and managing data in GIS.

Spatial data are managed in a GIS using the following two models:

- Raster Data:

A raster model is a way of storing geographic information in a two-dimensional grid of cells. Each cell is a square, and the size of the cells can vary from sub-meter to many kilometers. The value of each cell represents some attribute of the geographic area it represents, such as elevation, land cover, or temperature

- Vector Data

Vector format is a way of representing spatial data that uses coordinates to represent points, lines and polygons. This format is often used in GIS software because it is efficient to store and manipulate Entities in vector format are represented by strings of co-ordinates. Points on a map are stored with their exact coordinates. Lines are stored in the form of connected points and polygons are represented as a set of interconnected lines.

2. GIS Software

Modern GIS software has evolved significantly in recent years, becoming more powerful, versatile, and accessible than ever before. This development is due to numerous factors, including the rise of cloud computing, web-based GIS, and open-source GIS.

Cloud computing has made GIS software more accessible and affordable by allowing users to access GIS applications and data from any device with an internet connection. Web-based GIS has further democratized GIS by making it possible to use GIS software without having to install any software on a local computer. Open-source GIS has made GIS software more affordable and customizable by providing users with free and open-source GIS software and data.

In addition to these technological advances, the increasing availability of large datasets, such as those collected by satellites or drones, has also contributed to the evolution of modern GIS software. GIS software is now being used to analyze large datasets to gain insights into a wide range of phenomena, such as the spread of disease, the impact of climate change, and the movement of people and goods.

The evolution of modern GIS software is having a profound impact on the way we interact with the world around us. GIS software is now being used to solve a wide range of problems, from improving transportation to managing natural resources. As GIS software continues to evolve, it is likely to play an even greater role in our world in the years to come.

2.7 GIS and Decision Making Process

Geographic information systems (GIS) are powerful tools that can be used to integrate spatial data with decision-making processes. GIS can be used to visualize data, identify patterns, and analyze relationships between different variables. This information can then be used to make better decisions about a wide range of problems.

There are a number of ways to integrate GIS with decision making. One approach is to use GIS to create decision support systems (DSS). DSS are computer-based systems that help decision-makers make better decisions by providing them with access to information and analytical tools. GIS can be used to create DSS that help decision-makers visualize data, identify patterns, and analyze relationships between different variables.

Another approach to integrating GIS with decision making is to use GIS to create simulation models. Simulation models are computer models that are used to simulate the behavior of a system. GIS can be used to create simulation models that help decision-makers understand the impact of different decisions on a system.

The integration of GIS with decision making can be a complex process. However, the benefits of integrating GIS with decision making can be significant. GIS can help decision-makers make better decisions by providing them with access to information and analytical tools. This can lead to improved decision-making, which can benefit businesses, government agencies, and individuals.

2.7.1 Multi Criteria Analysis

Multi-Criteria Decision Making (MCDM) methods are used in the optimization of systems with multiple parameters taken into consideration at the same time (Akkas, et al., 2017). Multi-criteria analysis (MCA) has been used in energy planning for many years to address the increasing complexity of energy management problems. As (Pohekar & Ramachandran, 2004) has noted, traditional single-criteria decision-making approaches, which typically focus on maximizing benefits while minimizing costs, are often insufficient for these complex problems.

MCA methods provide a more comprehensive approach to decision-making by considering multiple criteria simultaneously. This allows decision-makers to better understand the inherent features of the problem, promote the participation of stakeholders, and facilitate compromise and collective decision-making. Additionally, MCA methods can help to improve the quality of decisions by making them more explicit, rational, and efficient.

(Velasquez & Hester, 2013) have identified the following MCDM methods to be in widespread use.

- Multi-Attribute Utility Theory (MAUT)
- Analytic Hierarchy Process (AHP)
- Case-Based Reasoning (CBR)
- Data Envelopment Analysis (DEA)
- Fuzzy Set Theory
- Simple Multi-Attribute Rating Technique (SMART)
- Goal Programming (GP)
- ELECTRE
- PROMETHEE
- Simple Additive Weighting (SAW)
- Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)

2.8 Use of MCDM in Solar PV Site Identification

AHP is one of the most widely accepted MCDM technique used by decision makers in multiple fields of business, economics, public policy development. Upon review of scholarly article regarding Solar PV site Identification, use of AHP was found to be extensive.

(Effat, 2013) utilized AHP for PV site selection in Egypt; (Uyan, 2013) used AHP analysis for feasibility study of solar farm in Konya, turkey (Tahri, et al., 2015) used AHP in to find optimum site for sitting solar PV in South, Morocco. Although AHP-TOPSIS, AHP-Fuzzy TOPSIS which are an extension over simple AHP have found their use in few research, their use hasn't gained widespread acceptance as AHP alone has. Upon review of following articles, it was realized than AHP based studies are more widely used and integrated in decision making problem involving solar PV site selection.

Table 2.2: Research conducted using AHP for Solar PV Site Selection

Sn.	MCDM Technique	Energy Sector	Location	Authors
1	AHP	PV	Ismailia, Egypt	(Effat, 2013)
2	AHP	PV	Konya, Turkey	(Uyan, 2013)
3	AHP	PV	United Kingdom	(Watson & Hudson, 2015)
4	AHP	PV	Indonesia	(Rumbayan, et al., 2012)
5	AHP	PV	South Morocco	(Tahri, et al., 2015)
6	AHP	PV	China	(Yunna & Geng, 2014)
7	AHP	PV	Serbia	(Doljak & Stanojević, 2017)
8	AHP	PV	Andalusia, Spain	(Carrion, et al., 2008)
9	FAHP	PV	Iran	(Noorollahi, et al., 2016)
10	FAHP	PV	Ulleung, Korea	(Suh & Brownson, 2016)
11	AHP-TOPSIS	PV	Cartagena, Spain	(Sánchez-Lozano, et al., 2015)
12	AHP-Fuzzy OWA	PV	Oman	(Gastli & Charabi, 2010)
13	AHP-Fuzzy TOPSIS	PV	India	(Sindhu, et al., 2017)
14	AHP-Fuzzy-WLC	PV	Isfahan, Iran	(Zoghi, et al., 2017)
15	AHP	PV	Madhesh province , Nepal	(Shrestha, et al., 2022)
16	FAHP-DEA	PV	India	(Lee, et al., 2017)

2.9 Analytical Hierarchy Process

(Saaty, 1990) introduced AHP during the 1990 and since then it has established itself as an indispensable tool in Decision making field. Instead of assigning weights directly to the criteria under study, AHP utilizes pairwise comparison between identified criteria using scale from 1-9, and produces results in the form of normalized weight through a defined mathematical model.

First of all, each criterion is evaluation in relation to one another pairwise and relative importance of one in contrast to another is identified as per the following table

Table 2.3: Criteria Evaluation Table (Saaty, 1990)

Intensity of importance	Characterization	Description
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, it dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

(Saaty, 1990) in his work emphasized the pairwise evaluation as critical in decision making, highlighting that, at a single time the decision makers are concerned only with two items of importance which makes the decision-making process simpler. He further aided the decision-making process by defining a consistency ratio, which aided the decision makers in making consistent decision by defining its upper limit at 10%. For any decision-making process, if the consistency ratio exceeds the limit of 10%, pairwise decisions are considered inconsistent in relation to one another and decision makers are required to reevaluate their decision and make necessary amendment.

The conceptual model behind AHP can be described as

1. Clearly define the unstructured problem into a defined one with criteria set for the supporting variable
2. Apply pairwise comparison among these criteria and set up a comparison matrix. Comparison matrix is simply a comparison table with criteria set in row and column, element of the matrix represents the relative scale of importance between row and column criteria.
3. Determine the Eigen vector and Eigen value of the comparison matrix. The real Eigen vector and its principal Eigen value are correspondingly the weights of the criteria and consistency index of the decision matrix.
4. Compute the consistency ratio of the decision matrix as
   CR = CI/RI, where CI = Consistency Index
   RI = Random Index (Value of random index)
5. If CR < 0.1 consider the decision matrix and consistent and if not repeat the process from step 1.

AHP has found its importance in a wide variety of decision-making process due to strong mathematical basis and ease of setting the comparison matrix. The obtained result from AHP can be utilized for overlaying the reclassified data in GIS application and obtaining a suitability map for land usage.

2.10 Site Selection Criteria

Site selection is a spatial problem that is affected by multitude of factors. The factors that seem critical for a particular region of interest may not be valid for another region while some criteria hold equally important for all the region.

(Rediske, et al., 2018) have identified the following six broad topics to be included during site selection research.

a) Socio-Environmental
   - Land use
   - Agrological capacity
   - Vegetation index
   - Expansion capacity
   - Visual Impact

- Population density
- Distance from main roads
- Distance from rail way network
- Distance from transmission lines
- Distance from residential area
- Distance from water resources
- Distance from protected region

b) Economic

- Cost of land
- Labor
- Economic Contribution
- Lifetime

c) Political

- Political incentives
- Rebates / Subsidies

d) Climate

- Solar radiation
- Average temperature
- Duration of sunlight
- Cloudiness
- Intensity of occurrence of natural disaster
- Wind speed
- Relative humidity

e) Orography

- Slope
- Guidance / Aspect

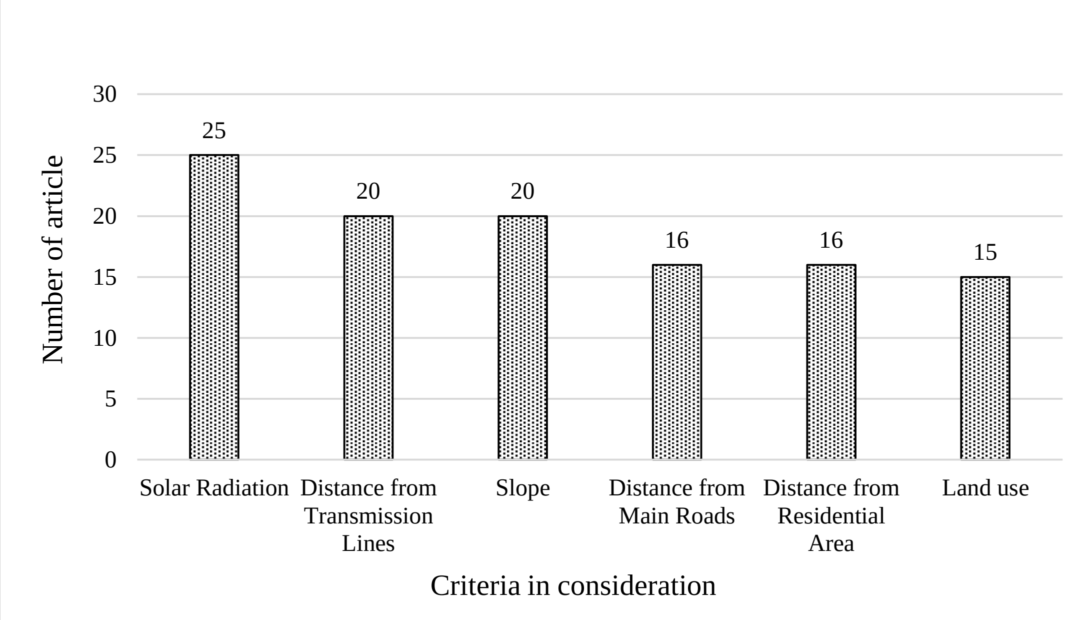

Figure 2.4: Articles with Criteria in consideration (Rediske, et al., 2018)

Large number of articles with criteria in consideration shown in Figure 2.4 shows solar radiation being used highest followed by distance from transmission lines and slopes (Rediske, et al., 2018). (Shrestha, et al., 2022) conducted similar type of research, specifically with site selection in Madhesh Province of Nepal and has identified the following (Table 2.4) criteria for site selection in the region.

Table 2.4: Site Suitability Criteria (Shrestha, et al., 2022)

Sn.	**Criteria**	**Explanation**
1	Solar radiation	Preference to higher solar irradiation
2	Annual mean temperature	Preference to lower temperature region
3	Distance from roads	Preference to area with close proximity to road
4	Distance from substation	Preference to region in close proximity to substation.
5	Distance from urban areas	Preference to area farther to residential areas

Sn.	Criteria	Explanation
6	Elevation	Preference to region with lower elevation
7	Slope	Preference to sites with lower slope
8	Aspect (orientation)	Preference to South Facing region.
9	Land Use	Preference to barren land

While (Shrestha, et al., 2022) have taken into consideration the distance between substation, proximity to transmission line has not been considered. Likewise, relative proximity to flowing river/water sources as a factor for site selection in context of Nepal seems to be important. Since water related incident and disasters are frequent in Nepal, so it seems natural to give due importance to proximity to water as a site selection criterion.

2.11 Classification of Criteria Attributes

Criteria have attribute range that determine its suitability. Upon systematic review of the following (Table 2.5) research articles, it was found that there exists a wide variation in the value of the criteria which makes quantifiable judgement based on these value extremely subjective.

(Yousefi, et al., 2018) proposed a distance of PV site from river within a range of 500m < x < 20 km as acceptable range while (Hafeznia, et al., 2017) proposed suitable distance from river as > 200m. For the same criteria (Noorollahi, et al., 2016) recommends suitable distance of >1000m from river.

Since there exist wide variations in the criteria attributes in previous researches, the attributes in this research has been classified following statistical distributions that minimizes variation within the same classification range and maximizes variations between multiple classification range using Jenks Natural Break Classification Method.

Table 2.5: Summary Of Research On Criteria Value/Range

Sn	Criteria	Reference	Preferable value/range
1		(Yousefi, et al., 2018)	> 4.5 $kWhr/m^2/day$

	Solar Irradiance	(Noorollahi, et al., 2016)	> 1300 kWhr/m^2/day
		(Zoghi, et al., 2017)	>1500 kWhr/m2/day
2	Slope	(Kereush & Perovych, 2017)	5 - 15 %
		(Suh & Brownson, 2016)	<18 %
		(Castillo, et al., 2016)	16 % - 30 %
3	Proximity to Transmission Lines	(Sindhu, et al., 2017)	< 3000 m
		(Noorollahi, et al., 2016)	< 50 km
		(Uyan, 2013)	< 3000 m
4	Distance from Settlement Area	(Yousefi, et al., 2018)	500m - 7 km
		(Merrouni, et al., 2017)	> 2000 m
		(Sindhu, et al., 2017)	> 500 m
5	Proximity to River	(Hafeznia, et al., 2017)	500 m - 20 km
		(Hafeznia, et al., 2017)	> 200 m
		(Noorollahi, et al., 2016)	> 1000 m
6	Distance to roads	(Yousefi, et al., 2018)	> 500 m acceptable
		(Merrouni, et al., 2017)	> 100 m
		(Noorollahi, et al., 2016)	100m - 50 km
7	Aspect	(Kereush & Perovych, 2017)	110-200
		(Watson & Hudson, 2015)	135 – 225

2.12 Identification of Criteria Significance in Solar PV Site Selection

The criteria as identified in (Table 2.5) needs to be ranked in order to determine the weightage as per AHP. For this a multiple research articles were reviewed, the ranking used in those research was then used as a basis to determine the ranking of the criteria in this research. A summary table consisting of past research in PV site selection is as follows.

Table 2.6: Summary of Research Article with Criteria Preference

Criteria \ References	(Carrion, et al., 2008)	(Effat, 2013)	(Uyan, 2013)	(Chen, et al., 2014)	(Vafaeipour, et al., 2014)	(Watson & Hudson, 2015)	(Tahri, et al., 2015)	(Sánchez-Lozano, et al., 2015)	(Brewer, et al., 2015)	(Noorollahi, et al., 2016)6	(Merrouni, et al., 2017)	(Sindhu, et al., 2017)	(Doljak & Stanojević, 2017)	(Fang, et al., 2018)	(Shrestha, et al., 2022)
Slope	3	-	-	5	-	-	2	5	2	5	2	-	2	3	7
Agricultural Area	5	-	1	4	-	-	5	3	-	6	-	6	1	4	9
Lakes and wetland	-	-	-	-	-	-	-	-	-	-	4	-	-	-	-
Rivers	-	-	-	-	-	-	-	-	3	-	3	-	-	-	-
Solar Radiation	1	1	-	1	2	1	1	2	1	1	1	2	3	2	1
Settlement Area	8	5	2	2	3	4	3	8	-	6	5	3	-	-	
Roads	7	4	3	3	4	3	4	7	2	5	7	1	-	5	3
Forest Area	6	-	-	-	-	3	-	-	-	-	-	4	-	-	
Aspect	4	2	4	7	-		3	6	-	-	-	-	4	3	8
Transmission	7	3	-	7	1	2	-	4	3	2	6	5	-	5	-
Elevation	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6
Earthquake	-	-	5	-	5	-	-	-	-	7	-	-	-	-	-
Sunshine Duration	2	-	-	-	-	-	-	-	-	-	-	-	5	1	-
Substations/ PowerStation	7	-	-	6	-	-	-	1	-	-	-	-	-	-	4
Temperature	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2

Chapter Three: Research Methodology

In this chapter, the research methodology applied for analyzing the site suitability problem is discussed in detail.

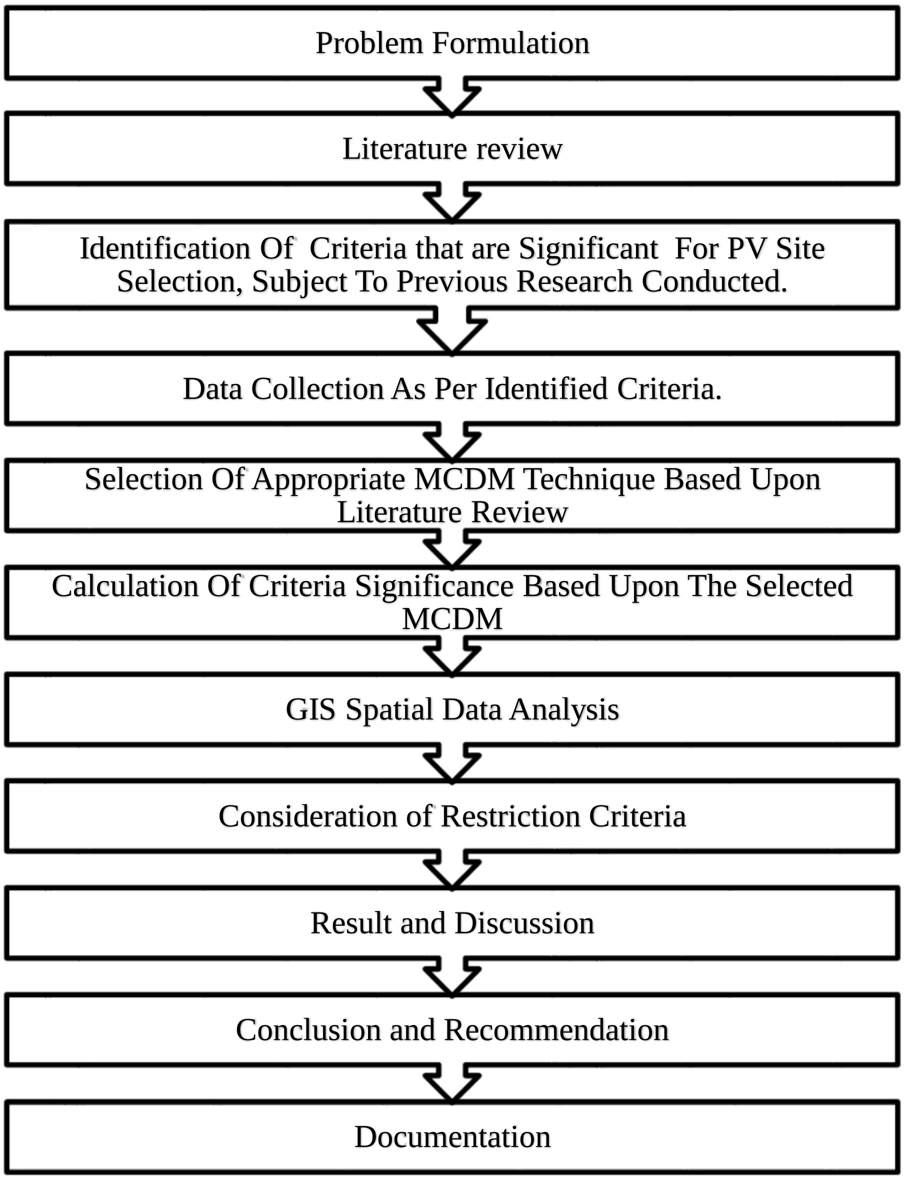

Figure 3.1: Overall Methodology

3.1 Criteria Identification and Selection Methodology

Based upon the review of prior research on PV Site Identification, the decision tree for selection of criteria is outlined as following.

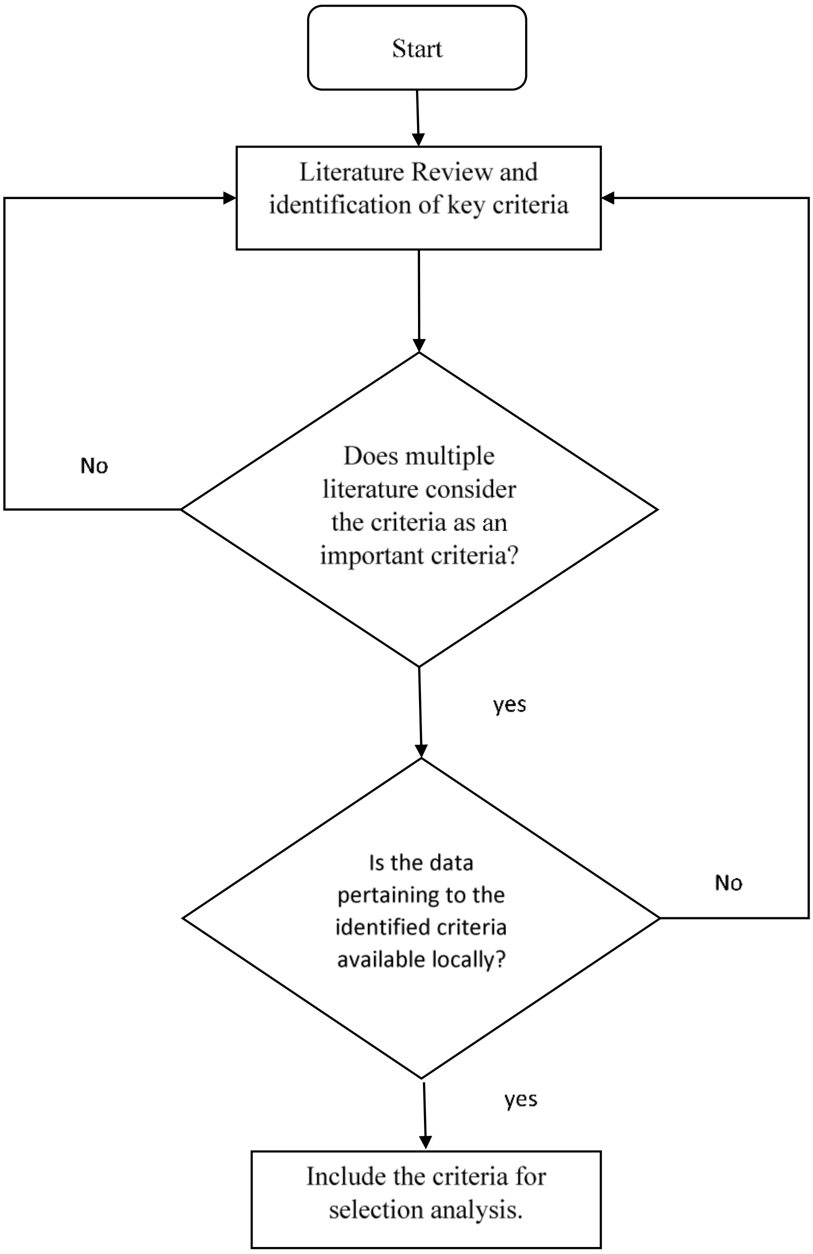

Figure 3.2: Decision Tree for Criteria Selection

Upon literature review conducted as per (Table 2.4), the following criteria were considered to be included in this research.

Table 3.1: Summary of the criteria considered in the scope for this research

Sn	Criteria	Sub-criteria	Explanation
1	Solar radiation	–	Preference to Sites with higher solar irradiation
2	Annual mean temperature	–	Energy production decreases as temperature increases beyond or below 25^{o}C. Areas closer to the optimum PV module working temperatures are preferred.
3	Distance from roads	Primary road	Sites closer to roads are given more preference
		Secondary road	
		Tertiary road	
4	Distance from Electric Grid/Sub-system	Distance from transmission lines	To decrease the cost of transmission infrastructures, sites near grid, substations and PowerStation are preferred.
		Distance from Sub-station	
		Distance from Power-Station	
5	Distance from Rivers	Primary River	Sites closer to the proximity of flowing river are prone to water related damages and incident
		Secondary River	
		Tertiary River	
6	Distance from Settlement	–	Preference is given to sites whose proximity to residential area is larger.
7	Elevation	–	Sites with lower elevation are preferred as its increases accessibility
8	Slope	–	Sites with smaller slopes are preferred to facilitate construction economy
9	Aspect (orientation)	–	South-facing sites are given more preference as they receive more solar irradiation.
10	Land Use	Barren Area	

Sn	Criteria	Sub-criteria	Explanation
		Agricultural Area	Sites on barren area are preferred than agricultural .
11	Restriction Area	Water bodies, Forest area, settlement area	Environmentally sensitive area (Forest, National Par, Conservation Area), settlement and water bodies are considered as restriction area. Solar PV site on these areas are restricted.

3.2 Data Collection Methodology

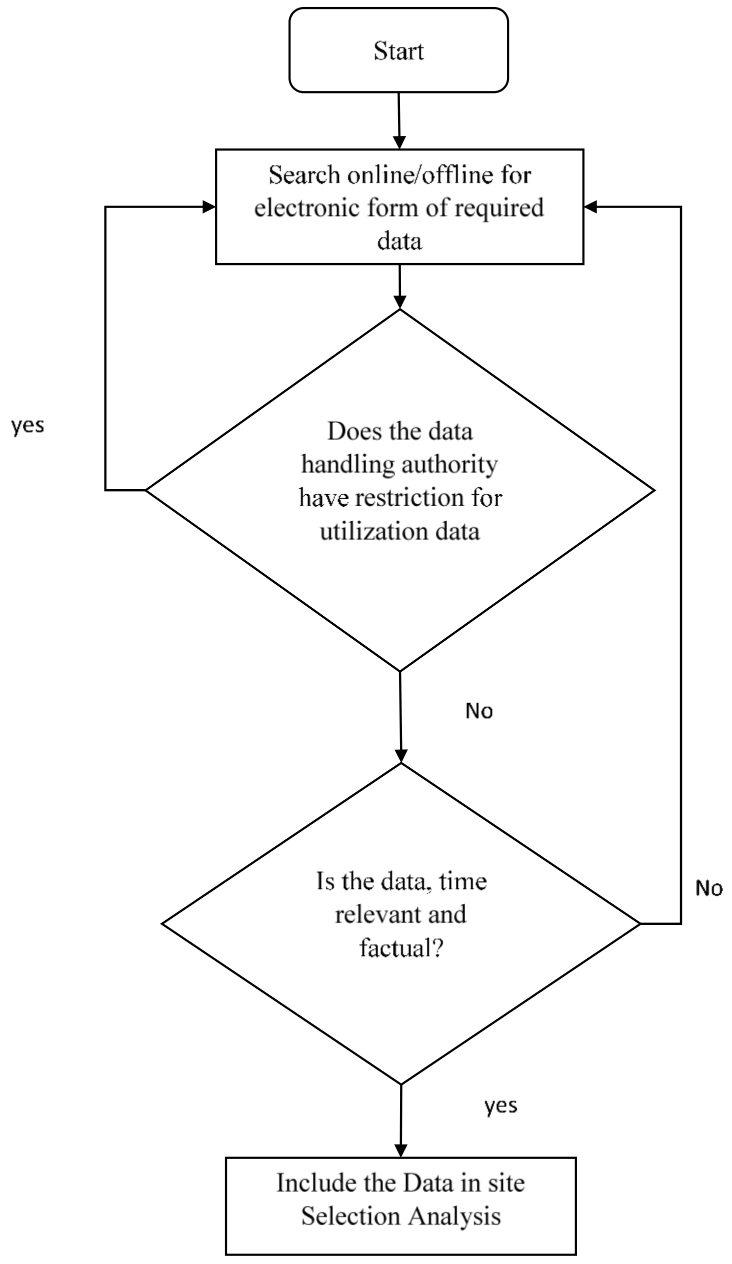

Figure 3.3: Data Collection Methodology

As identified in literature and summarized in (Table 4.1) the above data collection methodology was applied to obtain the secondary data for the research. The collected data for this research is tabulated below.

Table 3.2: List of Data Sources used

Criteria	Data Source	Data Type
Direct Normal Solar radiation	Remote sensing derived (resolution 250m*250m)	Raster
Slope / Gradient	Remote sensing derived (SRTM, 90m resolution)	Raster
Aspect	Remote sensing derived (SRTM GDEM DATA, 30m/90m resolution)	Raster
Hydrography	Department of Survey	Vector
Land use/cover	Land Use/Land Cover (LULC) data Department of survey	Raster
Grid Network/Sub-system	Ministry of Energy and Water Resources, Nepal Electricity Authority	Vector
Proximity to road network	Dept. of Survey	Vector
Environmentally Sensitive Areas (ESA) and Protected region	ICIMOD	Raster

3.3 MCDM Selection Methodology

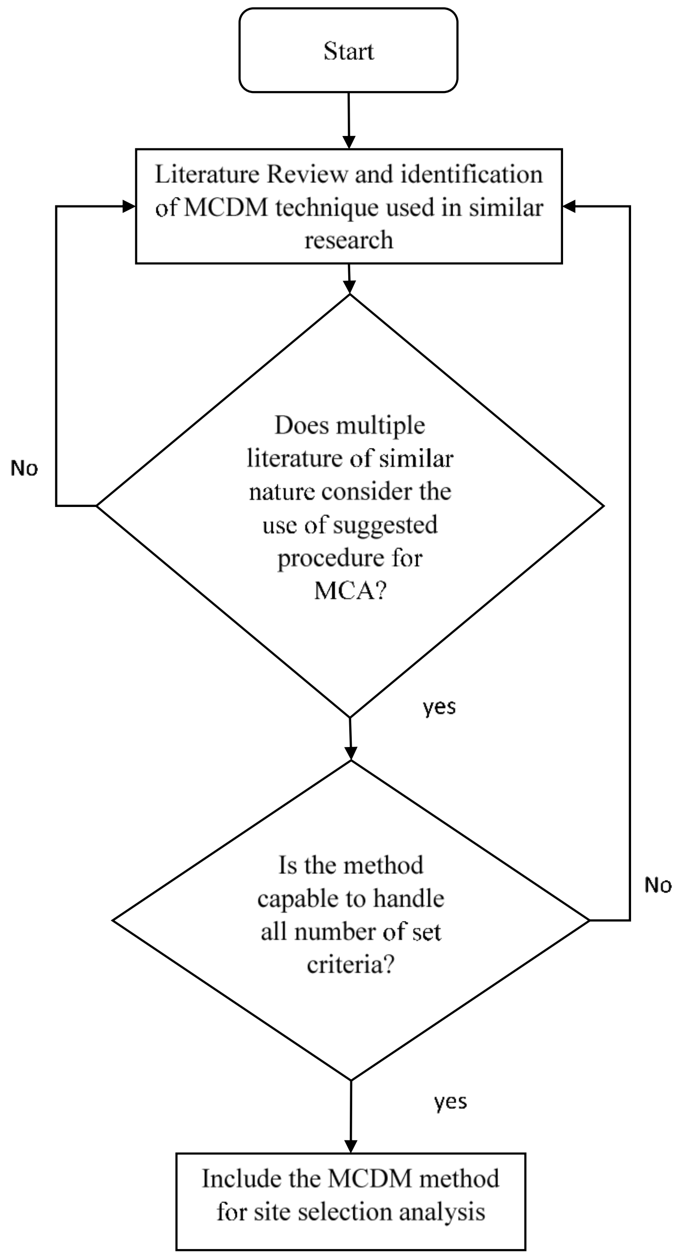

Figure 3.4: MCDM selection Methodology

After extensive literature review, it was found that AHP is the most widely used MCDM technique to ascertain site suitability for Solar PV plant installation (Table 2.2). The criteria set identified to be used in this research is well within the maximum of 10 criteria that can be utilized to calculate weightage using AHP.

3.4 Spatial Analysis Methodology

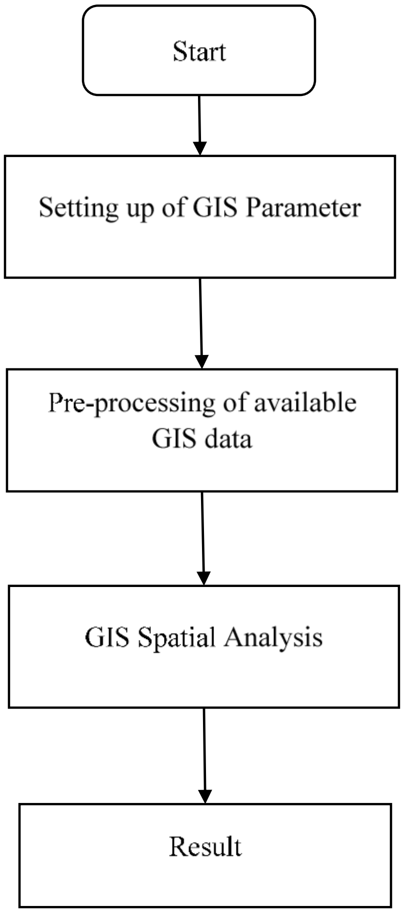

Figure 3.5: Spatial Analysis Methodology

3.4.1 GIS Parameters Setup

The project is initiated with the selection of appropriate Projected Coordinate System to be used. The selection of Projected Coordinate System is dependent upon the type of the GIS analysis to be done. Since this project primarily uses proximity analysis of various criteria, Projected Coordinate System that supports distance measurement in meters needs to be selected.

Similarly, the study area covers the entire region of Nepal, appropriate map projection needs to be used to account for minimum distortion.

The following parameters are used throughout the GIS analysis.

- Resolution: 100 m* 100m georeferenced
- Projected Coordinate System: ESRI 102306

3.4.2 GIS Data Pre-processing Methodology

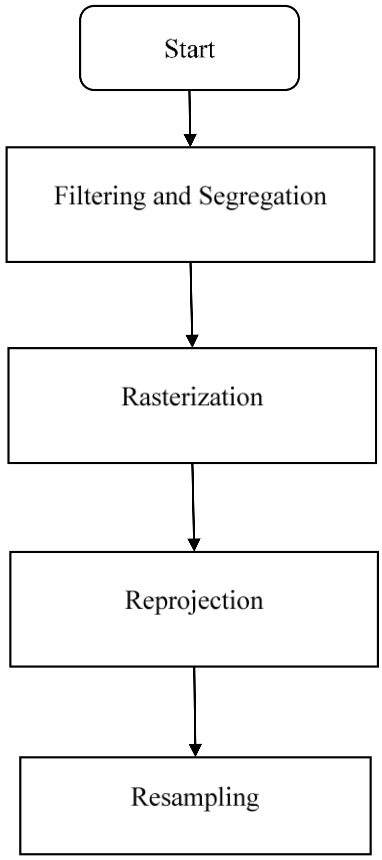

Figure 3.6: GIS Data Pre-processing Methodology

The preprocessing process is concerned with multiple operation of filtering/segregation, rasterization, re-projection and resampling of collected GIS data as per the requirement which is described below:

- Filtering/segregation: This project utilizes data collected from multiple sources which contains additional information in the form of attribute table. For e.g. The road network GIS data made available from Department of Survey, contains multiple roads data differentiated with attribute value. Filtering helps to remove unnecessary data prior to using the data so as to streamline the process.

a) Road Network is filtered and segregated into 3 different types of roads.

b) Hydrographical Network is also filtered into 3 different types based upon the Department of Survey grading system.

Similarly, the Landuse/Landcover data containing Forest and grassland, barren land, built-up area and agricultural area were segregated into separate and individual maps files to aid binary masking needed for GIS analysis.

- Rasterization: Rasterization is process of conversion of vector files into raster image where every pixel is of fixed georeferenced size, in this case 100 m * 100 m and contains information of that particular location such as minimum distance between next closest feature as in proximity map, elevation (in meter) for DEM, slope (in degree or percentage) for a particular location etc.

  All of the GIS analysis performed in this project is carried out for raster data. Weighted Overlay method is basically a linear combination of multiple raster value multiplied by a fixed constant (criteria weightage) which is used to produce the final site suitability map for Nepal. The following data in vector format is converted to raster data

  1. Road Network
  2. Hydrographical Network
  3. Transmission Grid Network
  4. Substation and PowerStation Network

- Resampling: Resampling is done in order to bring multiple raster to the same resolution so that raster operation can be applied correctly. Resampling means both up-sampling and down-sampling the input image to required size.

- Masking: Masking operation is used to capture a closed form of raster data using a vector shape. Masking is used to remove or extract a particular region of interest from a raster file. For e.g. Digital elevation data (DEM) is available in the form of rectangular grid and masking operation is used to capture the actual region of interest from the raster file through the help a vector file representing the area of interest.

  Solar Irradiance and Ambient Temperature Map available from SolarGIS for Nepal was released before the change in the political map of Nepal. As such, the data couldn't be utilized for this project directly. To solve this issue, solar irradiance and ambient temperature map for the entire South-Asian region from SOLARGIS was used. The map was re-projected to appropriate coordinate system and finally a vector masking operation was carried out to determine the GHI and temperature map for Nepal based on the new map.

3.4.3 Weighted Overlay Analysis Methodology

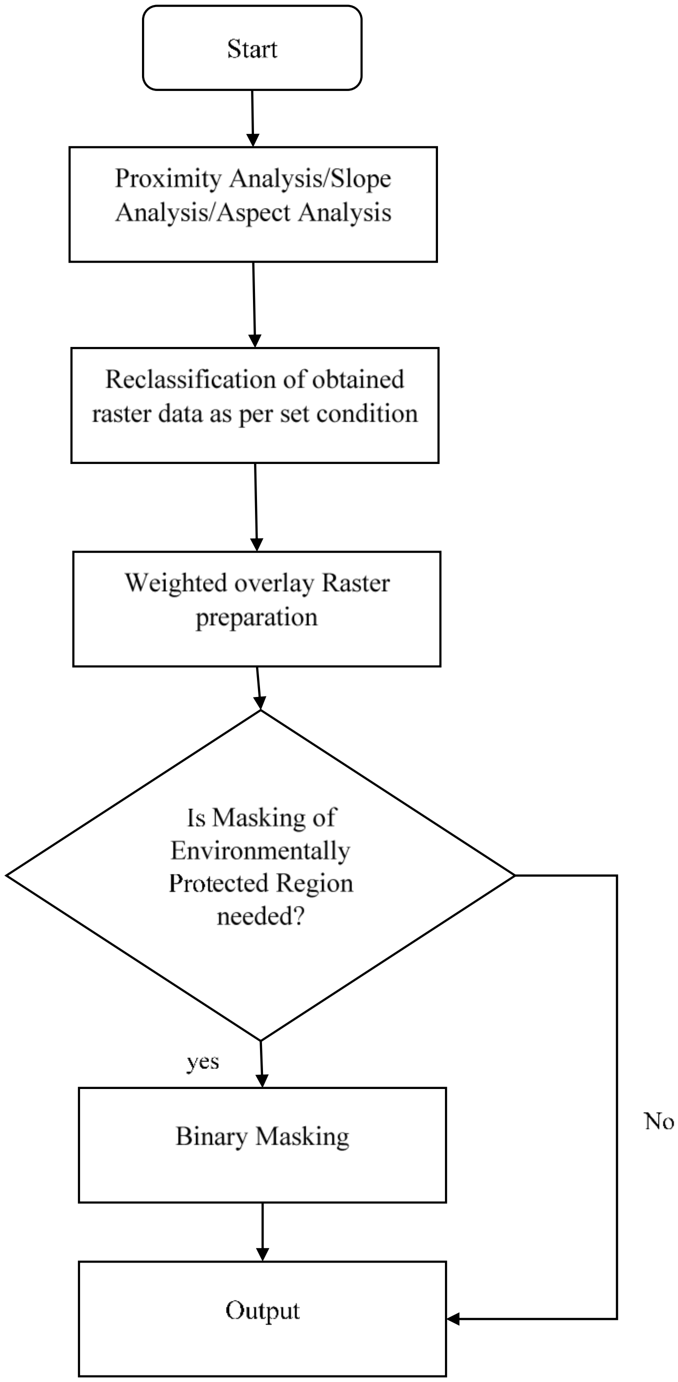

Figure 3.7: Weighted Overlay Analysis Methodology

After the preprocessing operation, the following raster data are available for further spatial processing.

- Road Network Raster Data
- Hydrographical Raster Data
- Transmission, PowerStation and Substation Raster Data
- DEM raster data for Nepal
- Annualized GHI raster Data
- Annualized Average Ambient Temperature Data
- Segregated Barren Land, Forest area, Cultivable area LULC raster data.

- **Aspect Analysis**:

Aspect Analysis is a common but complex GIS operation that takes DEM of the region of interest and returns a raster file where each pixel is a number that represents the orientation of the area in a range 0-360. 0 degrees represents North direction and 180 degrees represent south direction with east and west between them.

- **Slope Analysis**

Slope Analysis is another common GIS operation that also takes DEM of the region of interest and return a raster file where each pixel value corresponds to a number that represents the inclination or slope in a range 0- 90. 0 being flat ground and 90 being vertically steep area.

- **Proximity analysis**

Proximity analysis carries out Euclidean distance measurement between a point in a raster file and the closest features on the map. In short, each pixel value after proximity analysis represent the shortest distance between that point and the features under consideration.

Significance of Transmission Network, PowerStation and Sub-Station Network, hydrographical Network and Residential Area is carried out using Proximity Analysis.

- **Raster Reclassification**

Raster reclassification is a GIS technique to segregate large area into a fixed number of zone that helps to categorize it into region of highest significance to the zone of lowest significance. The output file after aspect, slope and proximity analysis is reclassified using Jenks classification using a scale of 1 – 5.

- **Weighted Overlay Calculation**

After the raster analysis of the criteria are completed, an overlay analysis was performed using the criteria weightage set as per (

Table **4.2**) to obtain a final site suitability map as following.

Site Suitability Map $= \sum_{k=0}^{n} w_k * R_k$, where w_k = weight of k^{th} criteria,

R_k = k^{th} Reclassified raster

3.5 Site Location Identification Methodology

The site suitability map obtained in the previous stage, is the input to this step. Usually, site location can be verified manually through visual inspection but when high resolution and large scale map is used, it quickly becomes infeasible to trace the actual location of the site.

An image processing clustering algorithm is utilized in GIS to find neighborhood pixel in a map. Multiple neighborhood pixels form an enclosed convex object whose centroid can be calculated to represent the site location.

This research uses DB-SCAN algorithm to segregate nearby pixel together to form a closed convex hull. The size of the convex hull is representative of the area of the pixel that it surrounds and thereby gives the estimate of the footprint of the plant.

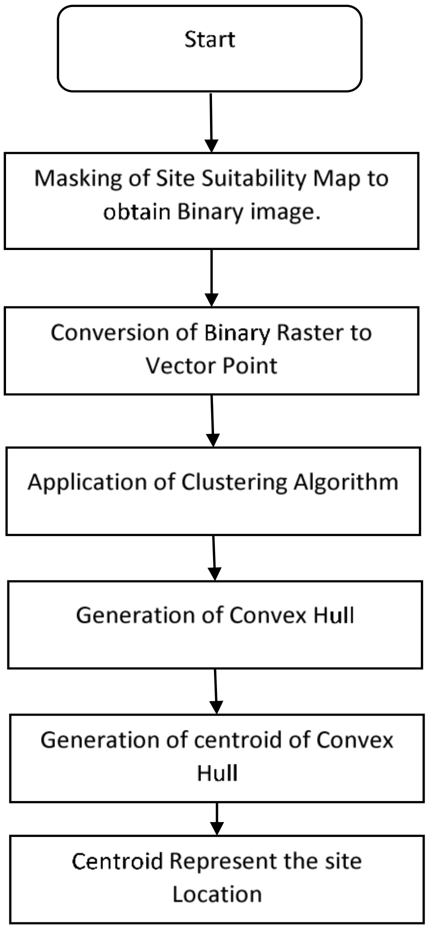

Figure 3.8: Location Identification Methodology

Chapter Four: Results and Discussion

The methodology proposed and explained in the previous chapter will be applied to the available data sets in a step by step manner in this part of the thesis and site suitability map shall be determined for the area of study.

4.1 Area under Study

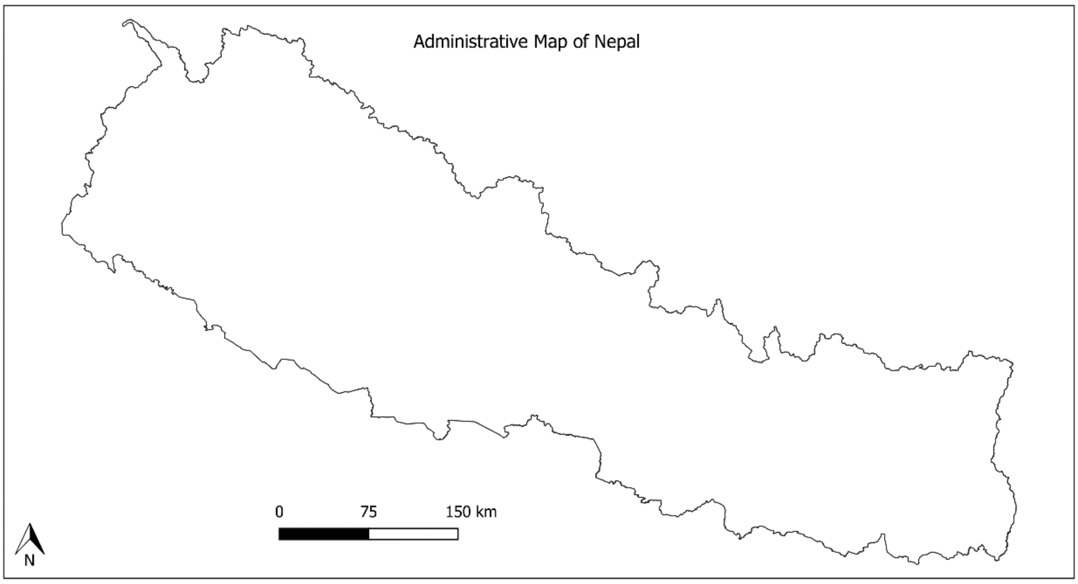

Figure 4.1: Administrative Map of Nepal

The study area covers the entire region of Nepal located between 26º and 31º north latitude, and between 80º and 89º east longitude. It has an area of about 147,516 square kilometers (km^2) and has extent of about 145–241 kilometers (km) north to south, and 850 km east to west. The altitude ranges from 100 meters to 8,848 meters. About 50% of total area is in the low-lying region in the south, about 43% in the hilly region and the remaining 7% in the Himalayan region.

4.2 Calculation of criteria weightage using AHP

AHP utilizes pairwise comparison between selected criteria to determine their weights. In order to formulate a paired comparison matrix, first of all priority list of the criteria needs to be determined. Upon referencing, (Table 2.6) the following priority list based on their significance was identified.

Table 4.1: Criteria Preference List

SN.	Criteria
1	Solar Irradiance
2	Slope
3	Electric Transmission Grid/Subsystem
4	Roads Network
5	River
6	Aspect
7	Human Settlement
8	Ambient Temperature
9	Elevation
10	Landuse/Landcover

Utilizing the above preference list of Table 4.1, a simple approach to create paired comparison matrix is detailed in (Table 8.1). Using this modality of paired matrix preparation, the consistency ratio is maintained at 0.05. A summary table for weightage calculation for the selected criteria/sub-criteria is outlined in

Table 4.2).

Table 4.2: Criteria Weightage Table

Sn	Criteria	Weightage	Final Weightage
1	GHI		0.2941

2	Slope		0.2151
3	Electrical Grid/Subsystem		0.1361
	Grid	0.53961455	0.0734
	Sub-Station	0.29696133	0.0404
	PowerStation	0.16342412	0.0222
4	Roads		0.1278
	Primary Road	0.53961455	0.0690
	Secondary Road	0.29696133	0.0380
	Tertiary Road	0.16342412	0.0209
5	Rivers		0.0760
	Primary River	0.53961455	0.0410
	Secondary River	0.29696133	0.0226
	Tertiary River	0.16342412	0.0124
6	Aspect		0.0532
7	Settlement		0.0373
8	Temperature		0.0264
9	Elevation		0.0192
10	Land use		0.0149
	Barren Area	0.743	0.0110
	Agricultural Area	0.257	0.0038

4.3 Reclassification Analysis

After the determination of weightage of every criterion as outlined in the methodology, the next step was to go through the pre-processed GIS data and carry out proximity and reclassification analysis.

The output from this procedure gives a reclassified raster of each criterion in the range 1-5 where 1 being least significant and 5 being extremely significant. The reclassified rasters were then used to produce a final, weighted overlay map showing suitable region for PV energy generation. The reclassification table and reclassified maps are included in appendix II.

4.4 Restriction Area Map

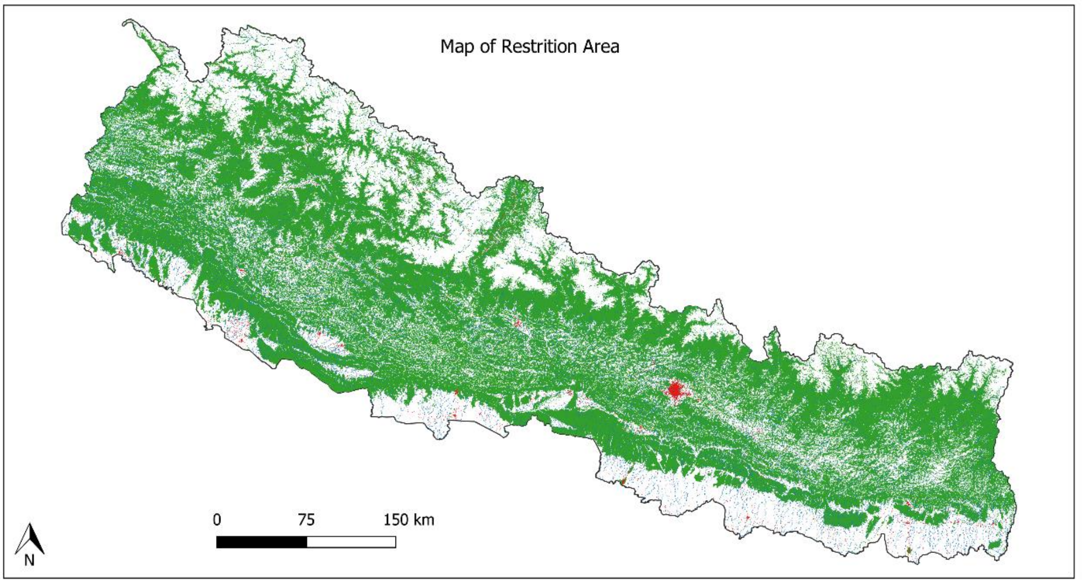

Figure 4.2: Restriction Area Coverage of Nepal

Forest, water bodies and Settlement area are together grouped as restriction criteria. This map (Figure 4.2) layer prepared to isolate region which is considered to be restricted for Solar PV site usage.

4.5 Site Suitability Map of Nepal

After the raster analysis of the criteria are completed, an overlay analysis was performed using the criteria weightage set as per (Table 4.2) to obtain a final site suitability map as following. The weighted overlay analysis results in a raster with value in a range of 1.35 – 4.14.

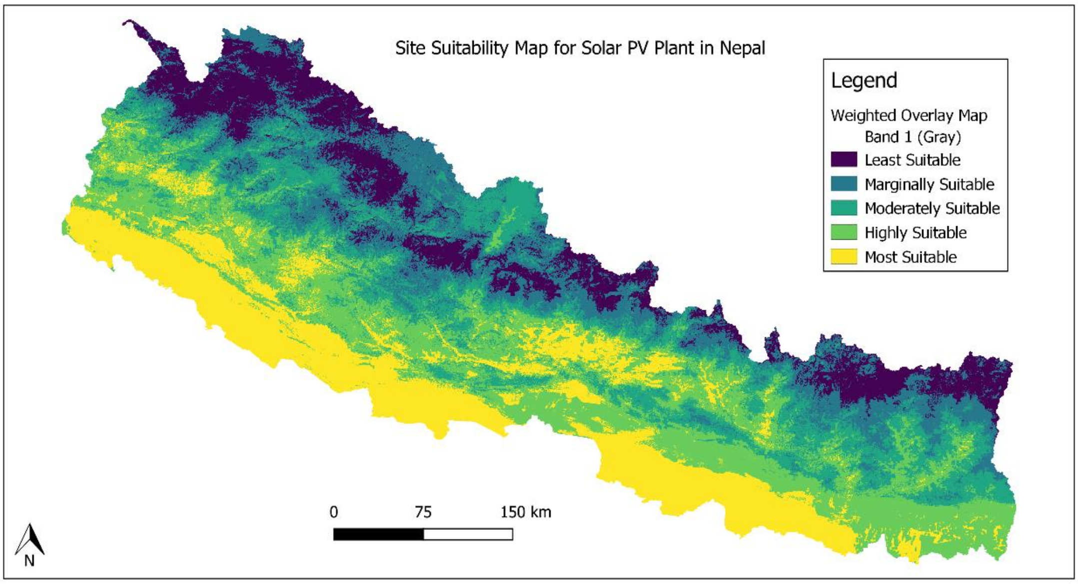

Figure 4.3: Weighted Overlay Site Suitability Map for Nepal

The threshold set for criteria such as proximity to highway, electrical Grid/Sub-system, elevation, temperature, aspect favors the region specifically in that region of Nepal. The region in the southern belt have the same geographical properties and shares similar trait in other criteria well too closely. The map thus produced (Figure 4.3) without considering any such restriction criteria clearly shows delineation of a large and almost continuous distribution of highly suitable region in the southern belt. This accounts for an area of 38980.78 sq. km which is 26.41% of coverage area (Table 4.4).

Table 4.3: Reclassification table for Site Suitability Map

Actual Value	Reclassified Value
< 2.37	Least Suitable
2.37 – 2.83	Marginally Suitable
2.83 – 3.27	Moderately Suitable
3.27 – 3.66	Highly Suitable
> 3.66	Most Suitable

As a whole, the zonal statistic of the above map (Figure 4.3) illustrates the following (Table 4.4) fact about the land suitability index and its corresponding coverage area providing 22.46% land occupying an 3315.17 sq. km as the most suitable area.

Table 4.4: Zonal Statistics of Site Suitability Map (Figure 4.3)

Sn.	Land Suitability Index	Area coverage Sq. Km	Percentage Coverage
1	Least Suitable	20378.56	13.80
2	Marginally Suitable	26449.53	17.92
3	Moderately Suitable	28665.21	19.42
4	Highly Suitable	38980.78	26.41
5	Most Suitable	33152.17	22.46

In the same way, if no restriction is imposed on the use of land, then highest of about 26.41 % percent of the total land area of Nepal with an area of 38980.78 sq. km classified under "Highly Suitable" region for solar PV energy generation.

4.6 Site Suitability Map of Nepal Considering Restriction Criteria

The site suitability map obtained earlier, Figure 4.3, is subjected to restriction criteria masking, where by region occupied forest area, water bodies and settlement area are completely isolated from the map to obtain the final map output. After this binary masking operation, the same reclassification range is used to obtain the following final map (Figure 4.4).

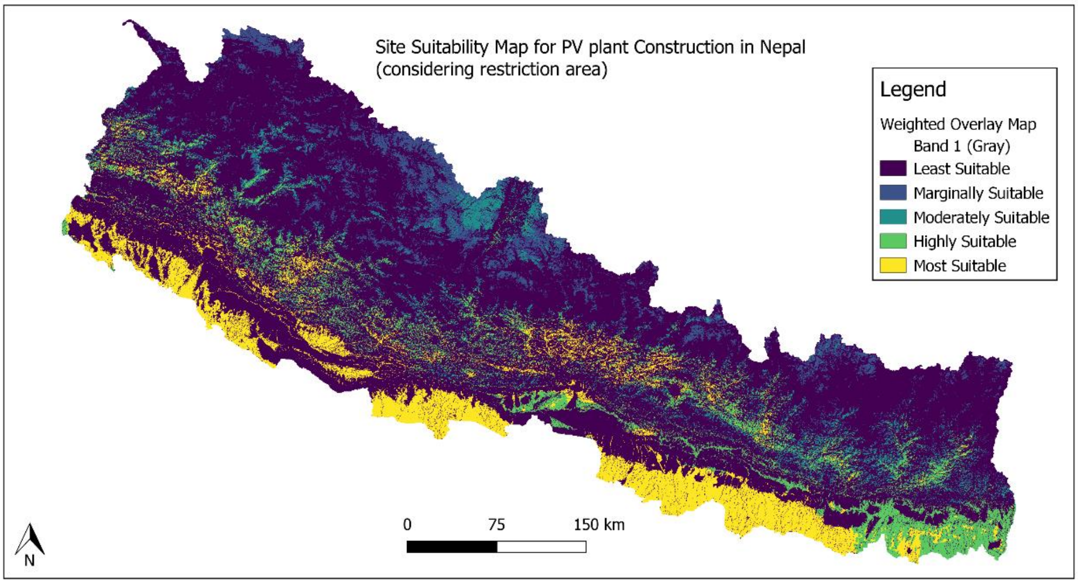

Figure 4.4: Site Suitability Map of Nepal considering Restriction criteria

From Figure 4.4 it can be observed that the "Most Suitable" region lies also primarily in the southern belt of Nepal. This region falls within majority of the cultivable area of Nepal. This gave an 8.71 % area coverage which is 12867.3 sq. km of land being "highly suitable" zones in Nepal. The details for zonal Statistics after consideration of restriction criteria are tabulated below in (Table 4.5) with "most suitable" area being 10.80 % which occupies an 15958.05 sq. km area of Nepal.

Table 4.5: Zonal Statistics of Site Suitability (Considering Restriction Criteria)

Sn	Land Suitability Index	Area Coverage (Sq. Km)	Percentage Coverage (%)
1	Least Suitable	103719.58	70.25
2	Marginally Suitable	8435.17	5.71
3	Moderately Suitable	6646.15	4.50
4	Highly Suitable	12867.3	8.71
5	Most Suitable	15958.05	10.80

4.7 Regional Distribution of Solar PV Suitable Sites

The overlay map obtained in (Figure 4.4) was further broken down at regional level to understand and analyze the distribution of site suitability at various provinces of Nepal. The following section discusses the site suitability of various provinces.

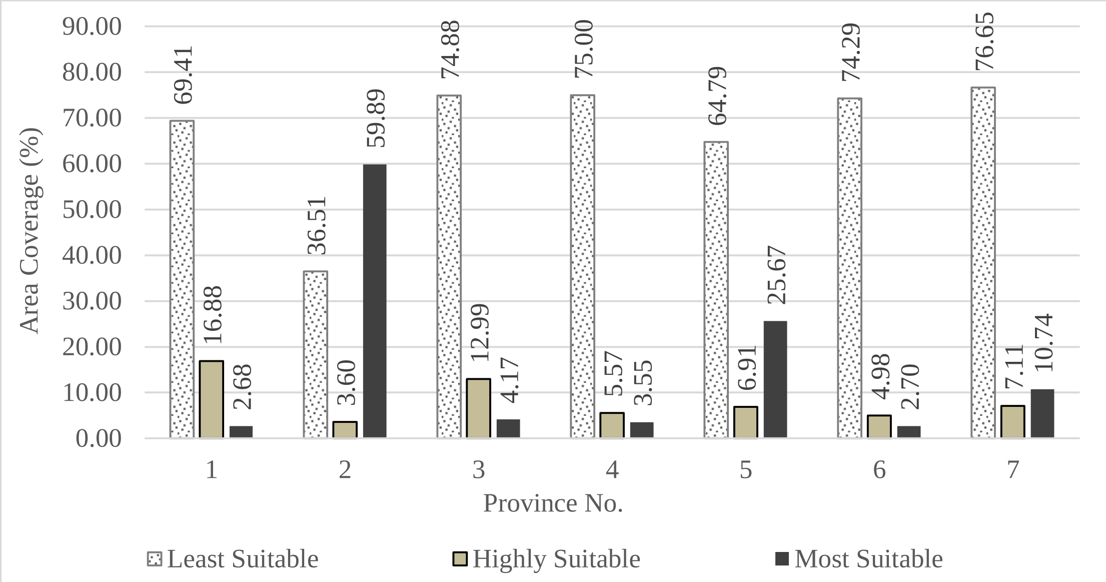

Figure 4.5: Percentage Coverage of suitability ranking across provinces

The province wise land suitability with restriction criteria showed province 2 and 5 as the most suitable, followed by province 3 and 1 having highly suitable lands whereas other province falls under least suitable categories in comparison. The detailed province wise suability maps and coverage area is in appendix III.

4.8 Potential Location Suitable for Construction of Utility Scale Solar PV Plant

The map from (Figure 4.4) is then subjected to features segmentation operation as per the methodology (Figure 3.8) to identify closely located landmass of Highly Suitable region throughout Nepal.

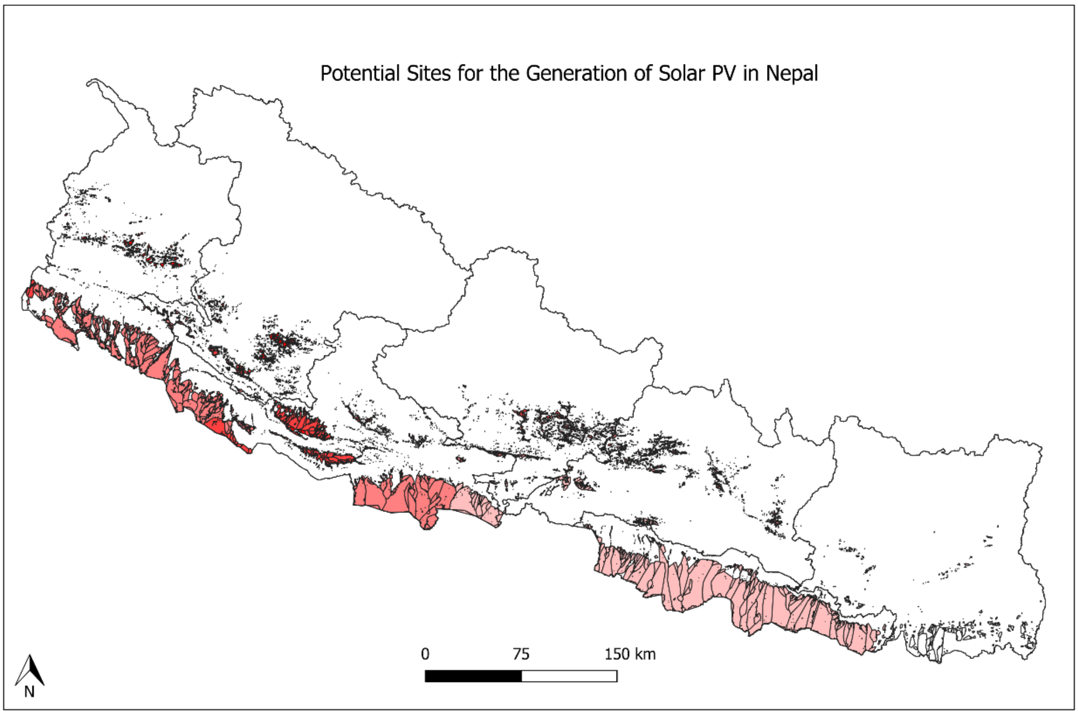

Figure 4.6: Site location for Solar PV energy Generation

After image segmentation, about 17,064 different locations with varying landmass and insolation potential was determined. The solar insolation potential of these regions were calculated based upon GHI and the area of the polygon calculated, represented in Figure 4.6.

As for the location for solar PV energy generation (Figure 4.6), majority of the southern region of Nepal have been identified as the area of most significance. Fragmented area can be observed in central, eastern and western region of the country.

Due to large image segmentation, large land mass of the southern region has been identified as potential region for PV generation but due to Land Usage requirement it cannot be realized in practice. Now, to segregate the attention to identify potential site with minimal outlier and extreme case value, the identified region in (Figure 4.6) were reclassified into 5 segments using Jenks Natural break Classification on the basis of their mean GHI and the following, Table 4.6 result was obtained.

Table 4.6: No. of Sites Located in specific GHI range

GHI Range (kWhr/m^2/day)	No of Sites identified
4.14 – 4.5	531
4.5 - 466	3602
4.66 – 4.79	6266
4.79 – 4.95	3751
4.95 – 5.24	2914

To focus the attention to the most suitable region, the 2914 sites in the insolation range 4.95-5.24 kWhr/m^2/day was taken into further consideration along with Table 4.7 results.

Table 4.7: Utility Scale PV Plant Footprint (Ong, et al., 2013)

Sn	Technology	Direct Area
		Capacity weighted average land use (sq. meter/MW_{ac})
1	Small Utility PV (> 1 MW, <20 MW)	
a	Fixed	23876.45288
2	Large PV (> 20 MW)	
b	Fixed	29137.36622

Out of the 2914 location segregated from region having highest GHI as shown in (Table 4.6) , the number of sites is further reduced to contain sites with area of greater than 23876 m^2 as per the utility scale pv plant footprint of Table 4.7, the minimum area required for sizing 1 MW_{ac} plant. The number of locations were reduced to 1376.

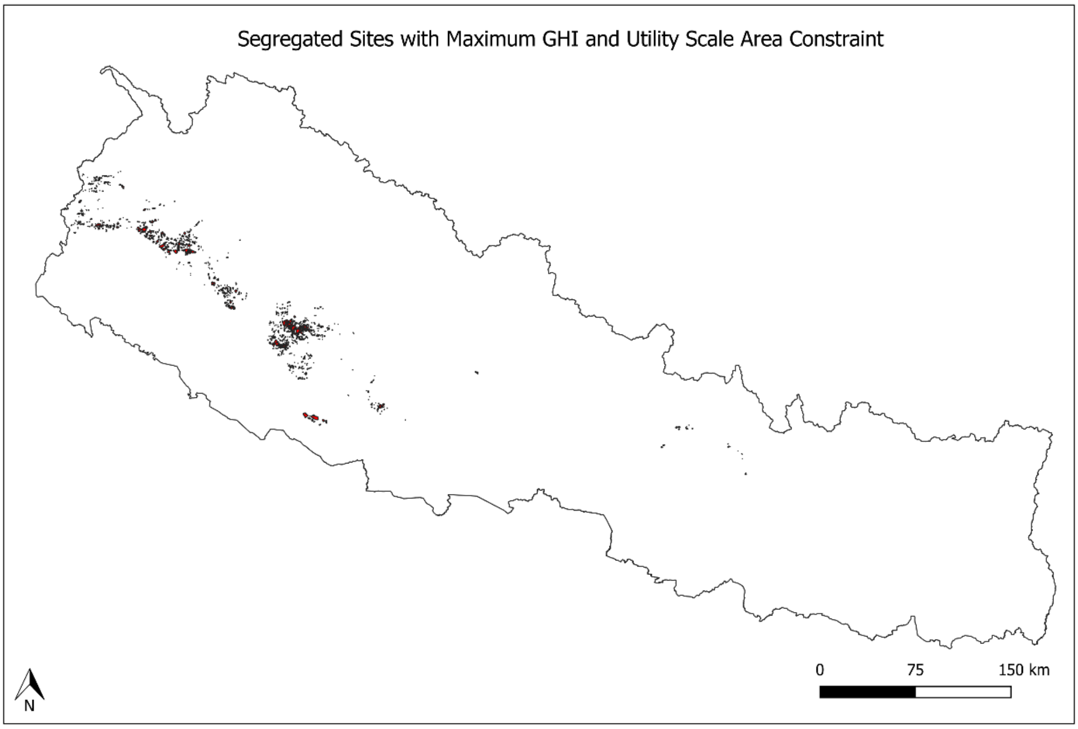

Figure 4.7: PV Site Location With Maximum GHI Range with Area Constraint

The details of locations with Maximum GHI Range with Area Constraint pertaining to Figure 4.7 is in (Table 4.8). A total of 1376 number of sites are suitable throughout the country occupying 56.235 sq. km.

Table 4.8: Statistics for Location with Maximum GHI Range with Area Constraint

No. of Utility Scale Sites	1376
Area Coverage	56.235 sq. km
Total Solar Irradiance over area	251.11 GWhr/day
Maximum Area of single site	11.335 sq km.

4.9 Discussion

Site suitability for Nepal without consideration of constraint (Figure 4.3, Table 4.4) shows 22.46% area of Nepal is “Most Suitable” area occupying 333152.17 sq. km of area. The largest area coverage is under "Highly Suitable" index with 26.41% coverage. It may be due to the fact that the region receives large solar irradiance and fulfill almost all of the criteria set during research initiation which is also discussed by (Suprova, et al., 2020) going through large number of literatures which considers solar irradiance to be one of the most significant factor for such suitability studies, followed by land slope, distance from main roads, also protected lands along with agricultural lands being highest restriction factors which are taken into considered in this study as well.

The research had expected to observe distributed/fragmented/segmented non-continuous distribution of suitable area. So that, segmentation of the zone to determine the coverage of each single unit of land mass could have been done. But since, there is a single large body of suitable region such segmentation would result in the formation of extremely big landmasses which would be extremely difficult to realize in real life. As (Suprova, et al., 2020) had also pointed out that when the work is about solar energy extraction in addition to climatic and geographic factors, features like environment, risks, community, and economy influences the technical, economical, viability, emission, land use, performance, efficiency and overall versatility. Thus, such factors play fundamental criteria role for solar site selection, and such factors severely effect decision-making processes for solar energy activities.

If no restriction is imposed on the use of land, then about 22.46 % percent of the total land area of Nepal is classified under "Most Suitable" region for solar PV energy generation. While Comparing this result with site suitability considering restriction criteria, it can be observed that there is huge incline in Least Suitable area of 103719.58 sq. km at 70.25%. It is due to the fact that forest area that covers nearly 44% of the total surface area of Nepal is considered as a restriction zone. Similarly, Built-up area and water bodies area also subtracted from the map, resulting in huge increase in the area of "Least Suitable Zone". The same reason is also responsible for reducing the "Most Suitable" area by almost a factor of 2, at 10.80% or 15958.05 sq. km. Similarly, reduction of "Marginally Suitable", "Moderately Suitable" and "Highly Suitable" area was observed by a considerable margin.

The high proportion of Least Suitable area in (Figure 4.4) is due to the consideration of constraint factor that is assumed by this research that solar PV sites are restricted to be built on environmentally sensitive and human settlement area (Al Garni & Awasthi, 2017).

Furthermore, for the case of regional distribution, Province-2, while being the smallest province, has the largest area that is suitable for Solar PV energy generation. Province-2 has the largest potential to generate energy from Solar PV from its 5711.58 sq. km of “Most Suitable” area while Province-1 has the least potential with only 696.67 sq. km area being “Most Suitable”. Similar study conducted by (Shrestha, et al., 2022) had also found that most of the region in Province-2 as being “Most Suitable” for PV energy generation. Province-2 highest potential can be attributed to high GHI across the southern belt, low elevation, flat topography, abundant road network and close proximity to Electrical Grid/Sub-system as well. The site selection criteria identified in this research favors Province-2 more than any other state. Although the primary contributor for the site suitability index is the GHI, the presence of other criteria also causes province-2 to remain high in the chart.

Province-2 and Province-5 shares the majority portion of “Most Suitable” site, with Province-5 occupying 30.99% of the total “Most Suitable” sites across the country (Figure 4.8). The condition for Province-5 being a close second is similar to Province-2 but Province-5 is almost double the size of province-2. The reason must be elevated region and hills/mountain area in larger existence in Province-5.

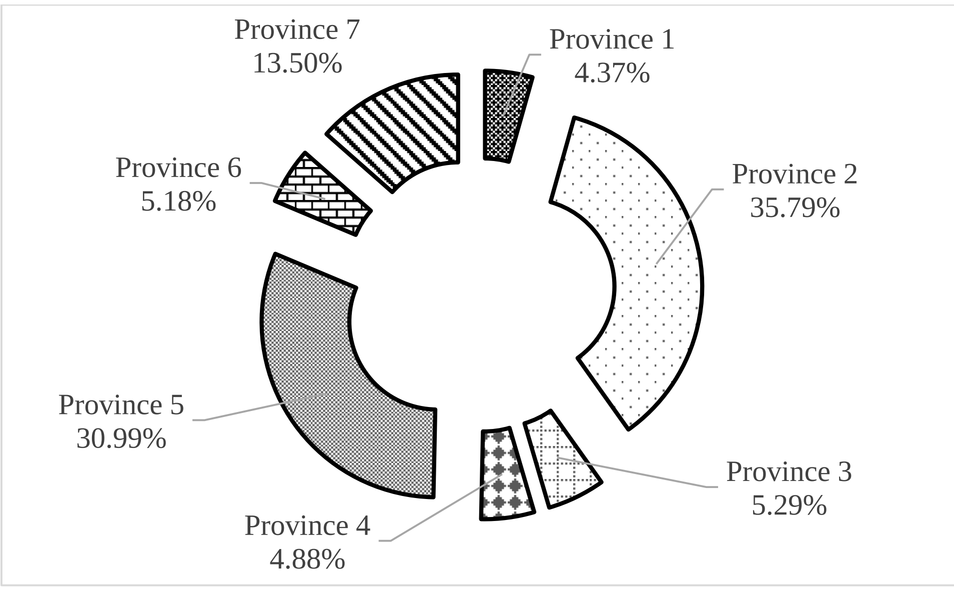

Figure 4.8:Distribution of "Most Suitable" Sites Across Provinces

It was observed that most of the optimal site was primarily located in the western region of Nepal, province 6 and 7 holding the larger share, province 5 in close third and finally followed by province-3 with very sparse regions. Noticeably, Province 2 was absent in this selection criteria, it is because the western region has more concentrated of GHI.

In order to identify actual site/location that is suitable for Utility Scale Solar PV plant construction, the "Most Suitable" area containing 17064 sites, from site suitability Map was again reclassified on the basis of its GHI (Table 4.1) into 5 classes using, Jenks Natural Break reclassification scheme. The higher classified region between (4.95-5.24 $kWhr/m^2/day$) is then taken as the subject of study, in doing so the identified location was maintained at. 2914. These sites were further reduced to 1376 by applying filter of Minimal Footprint area for Utility Scale Solar PV. In further calculation, about 56.235 sq. km of area was found to be utilized which would receive 251.11 GWhr/day of solar insolation.

Chapter Five: Conclusion and Recommendations

5.1 Conclusions

GIS based site suitability analysis for Solar PV energy generation in Nepal was conducted taking into account identified criteria which influence site selection. The contribution significance of the criteria was ranked referencing past research conducted in similar fields and quantified using Analytical Hierarchical Process. The maps of identified criteria were processed in GIS software and reclassified into a common 1-5 scale indicating their priority (1 being the lowest and 5 being the highest). Finally, raster GIS-based weighted overlay linear combination model was used in this study to identify, rank, and map areas within Nepal that are potentially suitable for PV energy generation.

About 10.80% of the country's area was found to be "Most Suitable" for solar PV energy generation while about 70.25% in the least suitable region. The Site Suitability map (Figure 4.4) provides overview of gross locations within Nepal which can be utilized to conduct a macro-scale GIS analysis for a particular region within Nepal or conduct an on-site field verification thereby reducing the preliminary cost associated with site survey.

Analysis of the Map (Figure 4.4) to regional level by studying the PV potential of various provinces in Nepal was also conducted. It was found that Province-2 has the highest potential of Solar PV energy while province-1 has the least potential. Upon further analysis it was found that, while province-2 has the largest area of "Most Suitable" region within it, few sparse regions in Province-6 and Province-7 were found to have region of Highest Solar PV potential.

The obtained suitability map was further analyzed for pin-pointing, "Most-Suitable" location suitable for construction of Solar PV plant. For this, the site suitability map was analysis though image segmentation and clustering algorithm, which identified total no. of 17,064 sites within Nepal. Due to the dense clustering of "Most Suitable" region in the southern belt, DB-SCAN algorithm caused the entire area in that region to be segregated into a single site with extremely large area. Thus, the site identification required much more fine grain control over the area, so GHI was taken as a parameter to segregate the clustered region into 5 segment and study the area of Highest GHI potential. This step reduced the potential region to 2940 sites. Further, it was reduced to 1376 sites by applying the nominal area constraint required for Utility Scale PV plant. In conclusion, an optimum number 1,376 identified sites with area coverage of 51.235 sq. km, with solar insolation potential of 251.11 GWhr/day could be generated in Nepal.

5.2 Recommendation

The land parcel in “Most Suitable” zone identified in this research can be investigated/research further at a micro-scale to segregate the area into multiple smaller region based on local and more relevant site selection criteria which can increase the effectiveness of site selection.

Aside from the land parcel, the 1376 specific location that have been identified in this research, could be a source of potential information public use

GIS based site selection procedure can be a beneficial tool for large-scale land suitability analysis. The effectiveness of GIS based research is however, limited by the availability of largescale, accurate and timely updated GIS data. Maintaining and updating such large scale data is a great endeavor which requires considerable financial burden. Government Initiation to maintain such record is inevitable to foster growth of GIS based research

Data pertaining to Road networks, Electric Grid/ Subsystem and land usage criteria used in this research are subject to change, so time relevant research can be done in case of availability of updated data.

As per the research findings, while large region of Province 2 was found to be suitable solar farming, taking into consideration the concentration of solar irradiance, Province 6 and 7 were found to be more suitable for utility scale solar PV production. Thus, appropriate policy level action to support research and enhancement of PV energy in these area is bound to bring measurable impact on energy sector and reduce the singular dependence on Hydro-power as the primary clean source of energy in Nepal.

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Appendices

Appendix-I: AHP Weightage Calculation

Table 8.1: Pairwise comparison Matrix for Major Criteria

Matrix	GHI	Slope	Electrical Grid/Subsystem	Roads	Rivers	Aspect	Settlement	Temperature	Elevation	Land use
GHI	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	9.00
Slope	0.50	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
Electrical Grid/Subsystem	0.33	0.50	1.00	0.50	3.00	4.00	5.00	6.00	7.00	8.00
Roads	0.25	0.33	2.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00
Rivers	0.20	0.25	0.33	0.50	1.00	2.00	3.00	4.00	5.00	6.00
Aspect	0.17	0.20	0.25	0.33	0.50	1.00	2.00	3.00	4.00	5.00
Settlement	0.14	0.17	0.20	0.25	0.33	0.50	1.00	2.00	3.00	4.00
Temperature	0.13	0.14	0.17	0.20	0.25	0.33	0.50	1.00	2.00	3.00
Elevation	0.11	0.13	0.14	0.17	0.20	0.25	0.33	0.50	1.00	2.00
Land use	0.11	0.11	0.13	0.14	0.17	0.20	0.25	0.33	0.50	1.00

Table 8.2: Weightage Calculation of Primary Criteria

Criteria	Weightage
GHI	0.29
Slope	0.22
Electrical Grid/Subsystem	0.14
Roads	0.13
Rivers	0.08
Aspect	0.05
Settlement	0.04
Temperature	0.03
Elevation	0.02
Land use	0.01

Consistency Ratio	0.05

Table 8.3: Pairwise comparison matrix of River Network

Matrix	Primary River	Secondary River	Tertiary River
Primary River	1.00	2.00	3.00
Secondary River	0.50	1.00	2.00
Tertiary River	0.33	0.50	1.00

Table 8.4: Weightage of River Network

Criteria	Weightage
Primary River	0.53961455
Secondary River	0.29696133
Tertiary River	0.16342412

Consistency Ratio	0.01

Table 8.5: Pairwise Comparison Matrix of Road Networks

Matrix	Primary Road	Secondary Road	Tertiary Road
Primary Road	1	2	3
Secondary Road	0.5	1	2
Tertiary Road	0.33	0.5	1

Table 8.6: Weightage for Road Network

Criteria	Weightage
Primary Road	0.53961455
Secondary Road	0.29696133
Tertiary Road	0.16342412

Consistency Ratio	0.01

Table 8.7: Weight Calculation of LULC

Criteria	Weightage
Barren Area	0.743 (Shrestha, et al., 2022)
Agricultural Area	0.257 (Shrestha, et al., 2022)

Appendix-II: Proximity and Reclassification Analysis

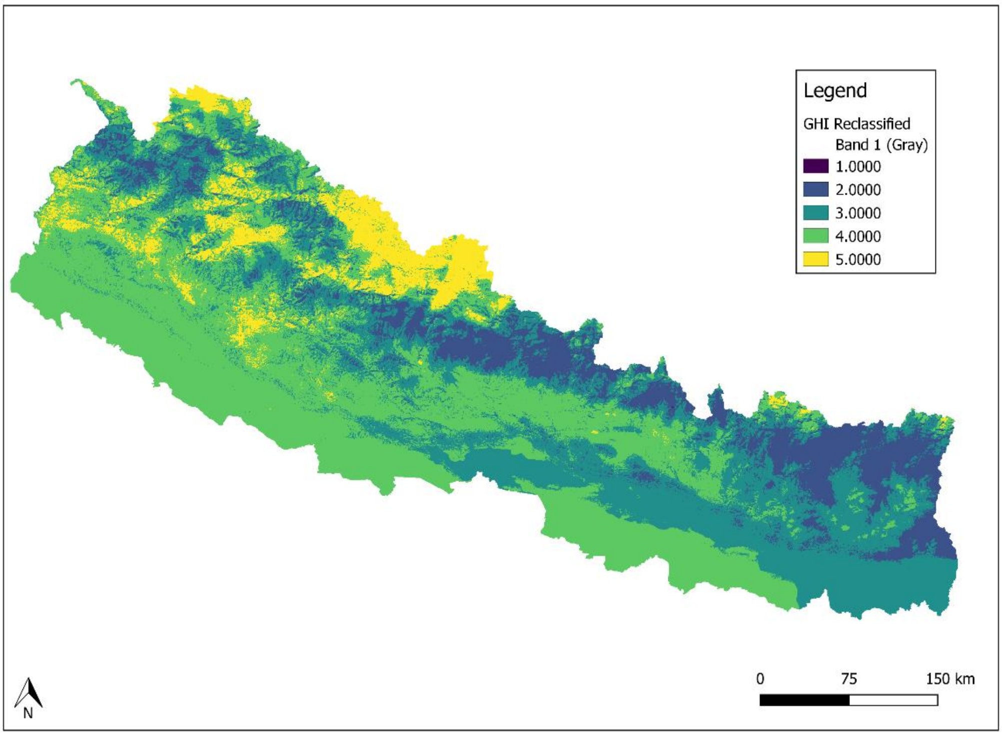

Figure 9.1: Reclassified GHI Distribution Map of Nepal

Table 9.1 Reclassification Table for Solar Irradiance

Actual Values (kWhr/m^2/day)	Reclassified Values
<1.8701	1
1.8701-4.0635	2
4.0635-4.5294	3
4.5294-4.9849	4
>4.9849	5

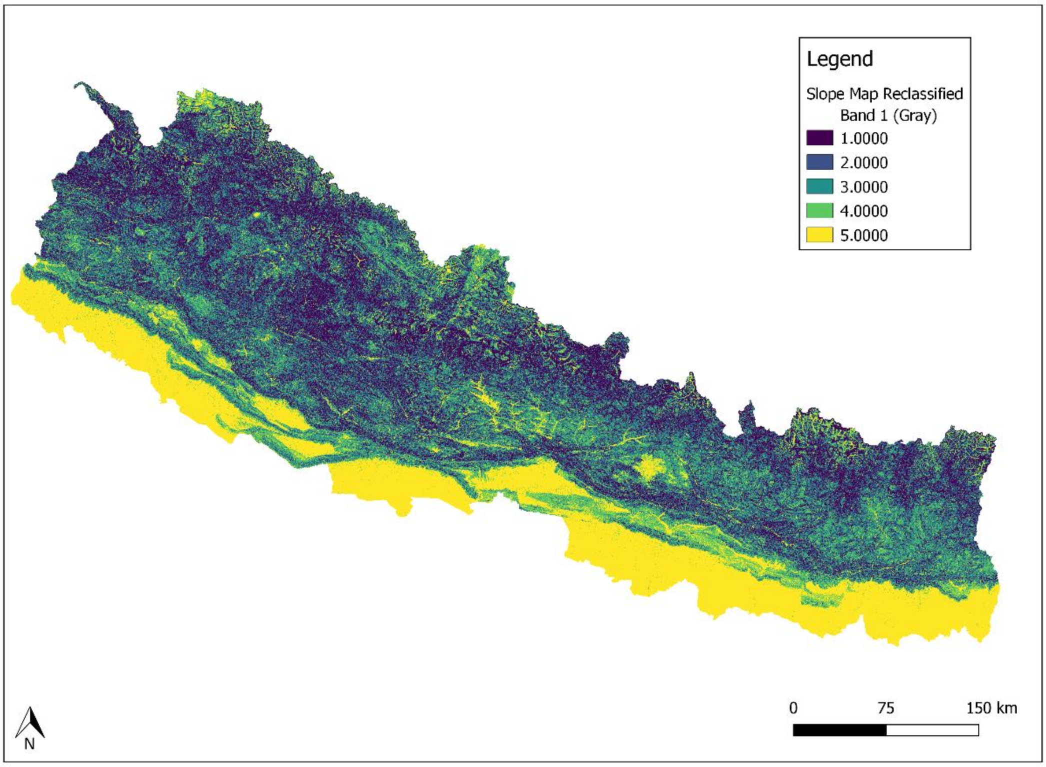

Figure 9.2: Reclassified Slope Distribution Map of Nepal

Table 9.2 Reclassification Table (Slope Map)

Actual Values (degree)	Reclassified Values
< 7.086	5
7.086 – 18.731	4
18.731 – 26.886	3
26.886 – 34.237	2
> 34.237	1

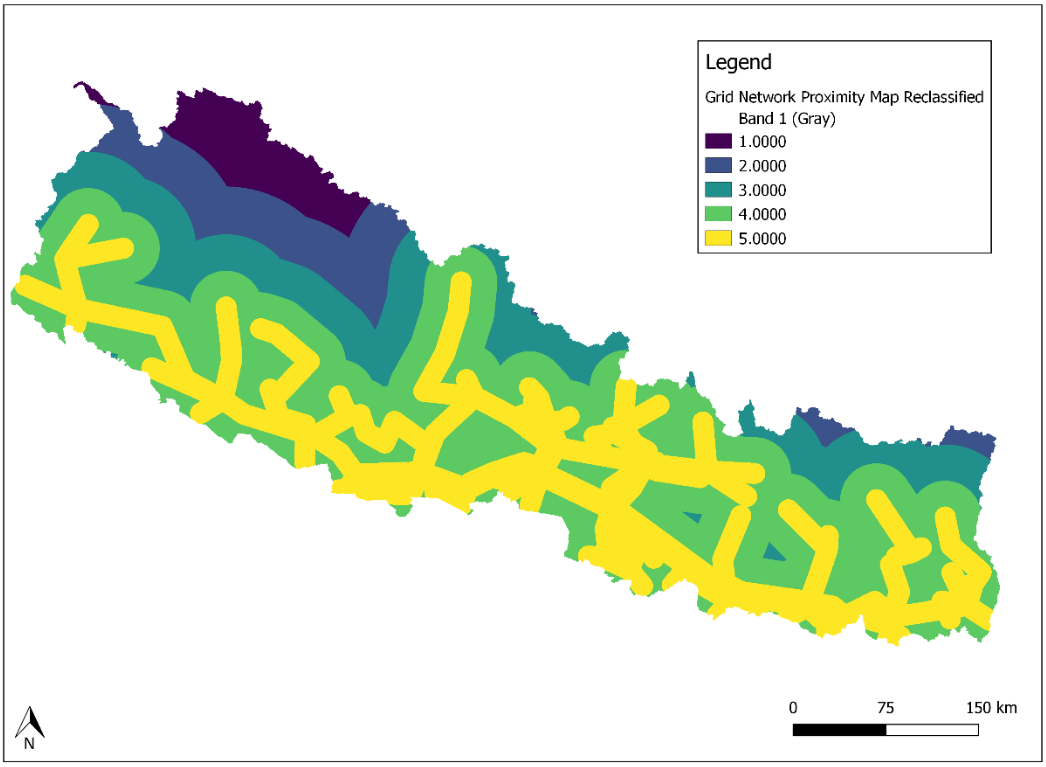

Figure 9.3: Reclassified Proximity Distribution of Electrical Grid Network of Nepal

Table 9.3 Reclassification Table (Grid Network)

Actual Values (meter)	Reclassified Values
< 8476.40	5
8476.40 – 29350.72	4
29350.72 – 58752.06	3
58752.06 – 97520.28	2
> 97520.28	1

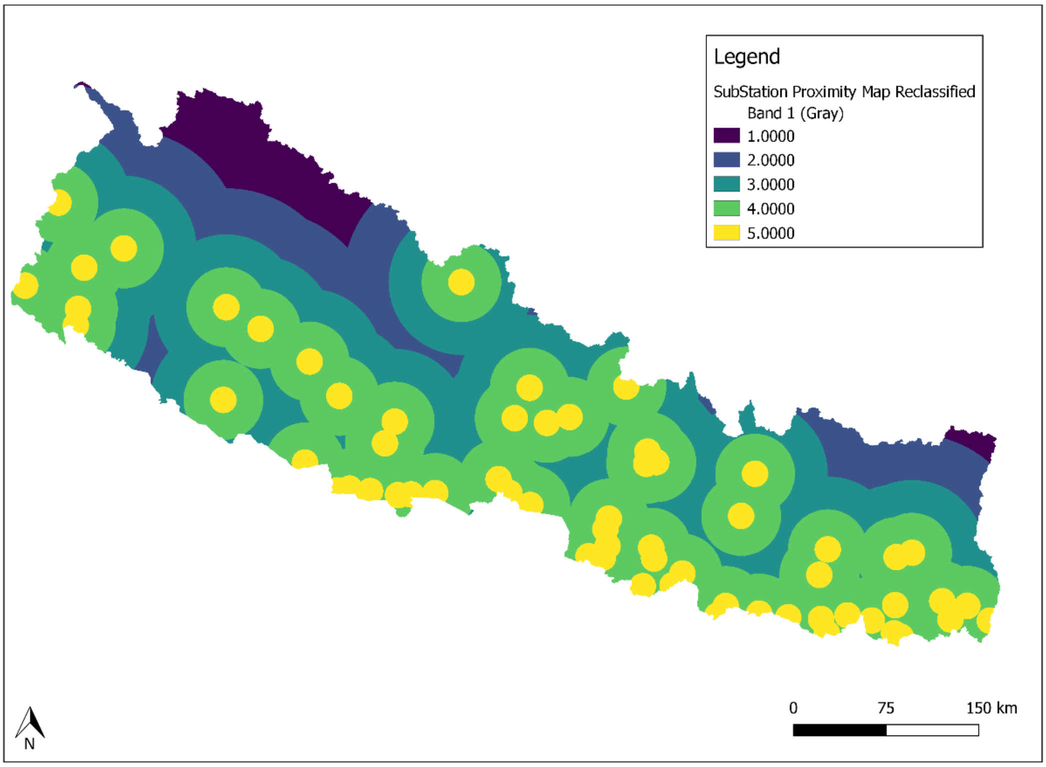

Figure 9.4: : Reclassified Proximity Distribution of Electrical Substation of Nepal

Table 9.4 Reclassification Table (Sub-station)

Actual Values (meter)	Reclassified Values
< 10760.35	5
10760.35 – 32349.57	4
32349.57 – 58934.67	3
58934.67 – 96226.48	2
> 96226.48	1

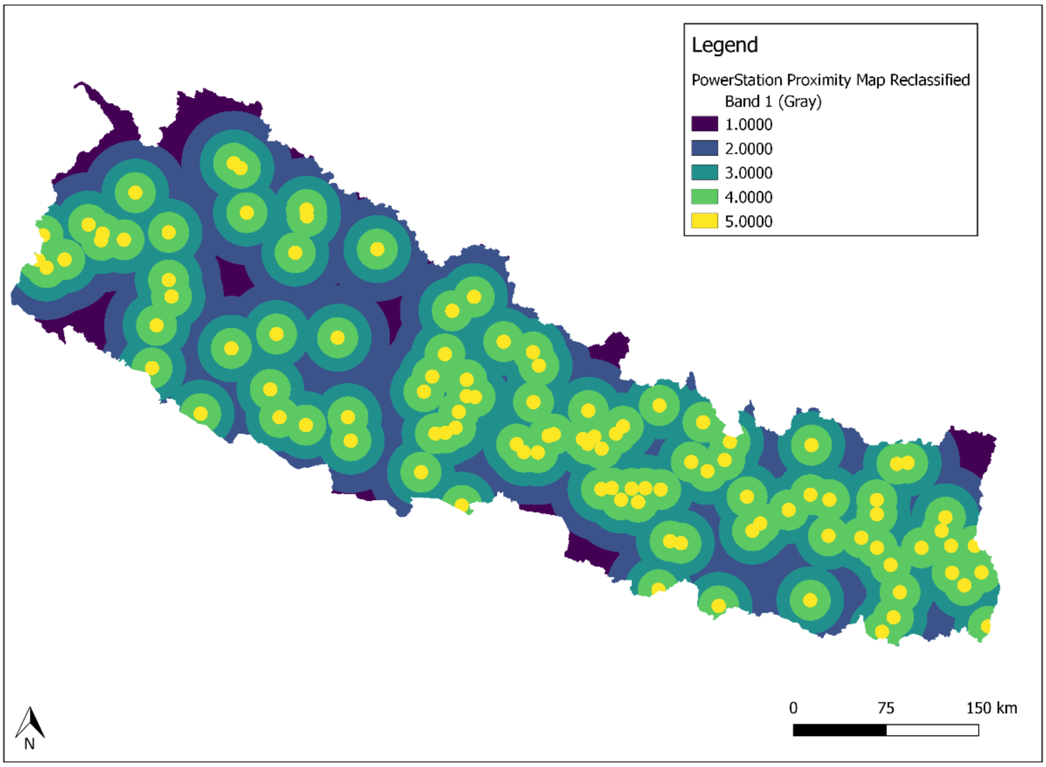

Figure 9.5: Reclassified Proximity Distribution of PowerStation Network of Nepal

Table 9.5 Reclassification Table (PowerStation)

Actual Values (meter)	Reclassified Values
< 5794.5	5
5794.5 – 16609.18	4
16609.18-27454.23	3
27454.23 – 42406.78	2
> 42406.78	1

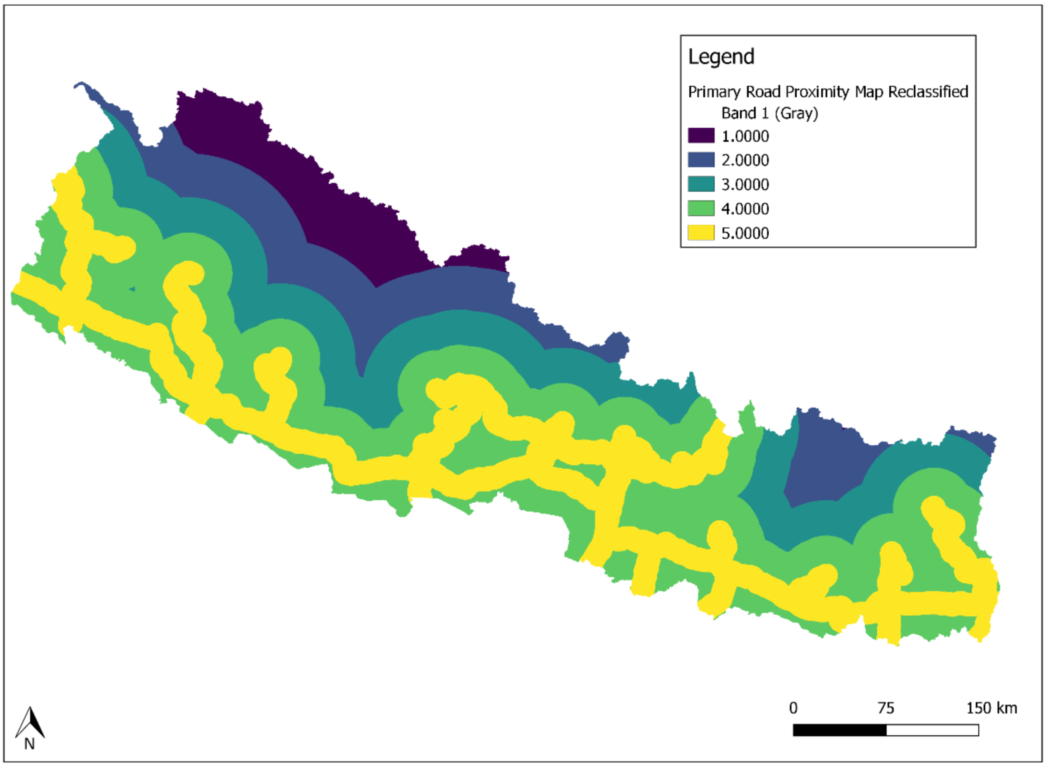

Figure 9.6: Reclassified Proximity Distribution of Primary Road Network of Nepal

Table 9.6 Reclassification Table (Primary road)

Actual Values (meter)	Reclassified Values
< 9381.10	5
9381.10 – 32064.54	4
32064.54 – 60589.89	3
60589.89 – 96000.91	2
> 96000.91	1

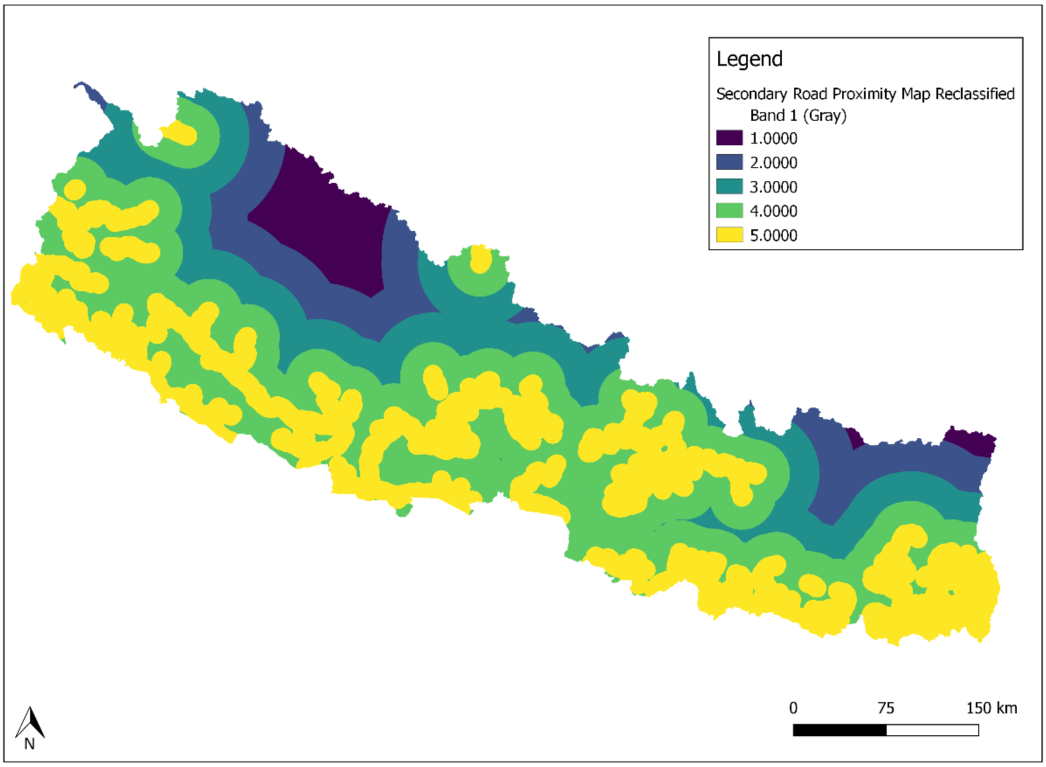

Figure 9.7: Reclassified Proximity Distribution of Secondary Road Network of Nepal

Table 9.7 Reclassification Table (Secondary road)

Actual Values (meter)	Reclassified Values
< 7829.75	5
7829.75 – 26324.61	4
26324.61 – 50273.40	3
50273.40 – 79828.17	2
> 79828.17	1

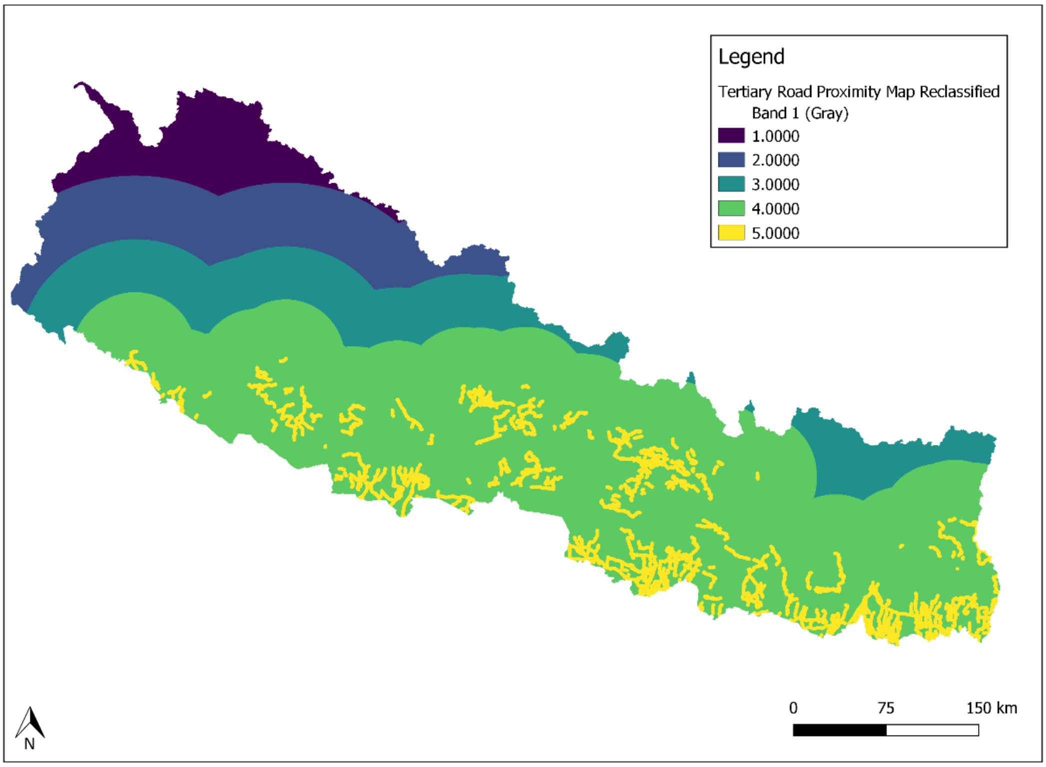

Figure 9.8: Reclassified Proximity Distribution of Tertiary Road Network of Nepal

Table 9.8 Reclassification Table (Tertiary road)

Actual Values (meter)	Reclassified Values
<1447.89	5
1447.89 – 47741.96	4
47741.96 – 90660.55	3
90660.55 – 142225.47	2
> 142225.47	1

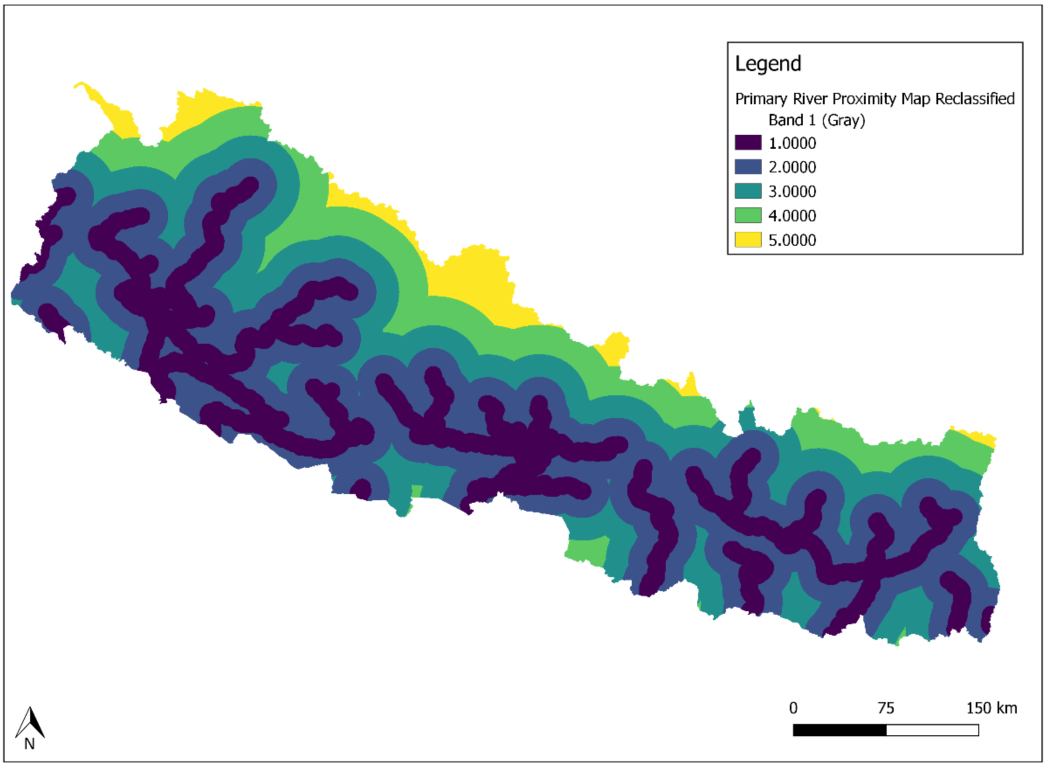

Figure 9.9: Reclassified Proximity Distribution of Primary River Network of Nepal

Table 9.9 Reclassification Table (Primary river)

Actual Values (meter)	Reclassified Values
< 6894.57	1
6894.57 – 21538.22	2
21538.22 – 39906.58	3
39906.58 – 63596.42	4
> 63596.42	5

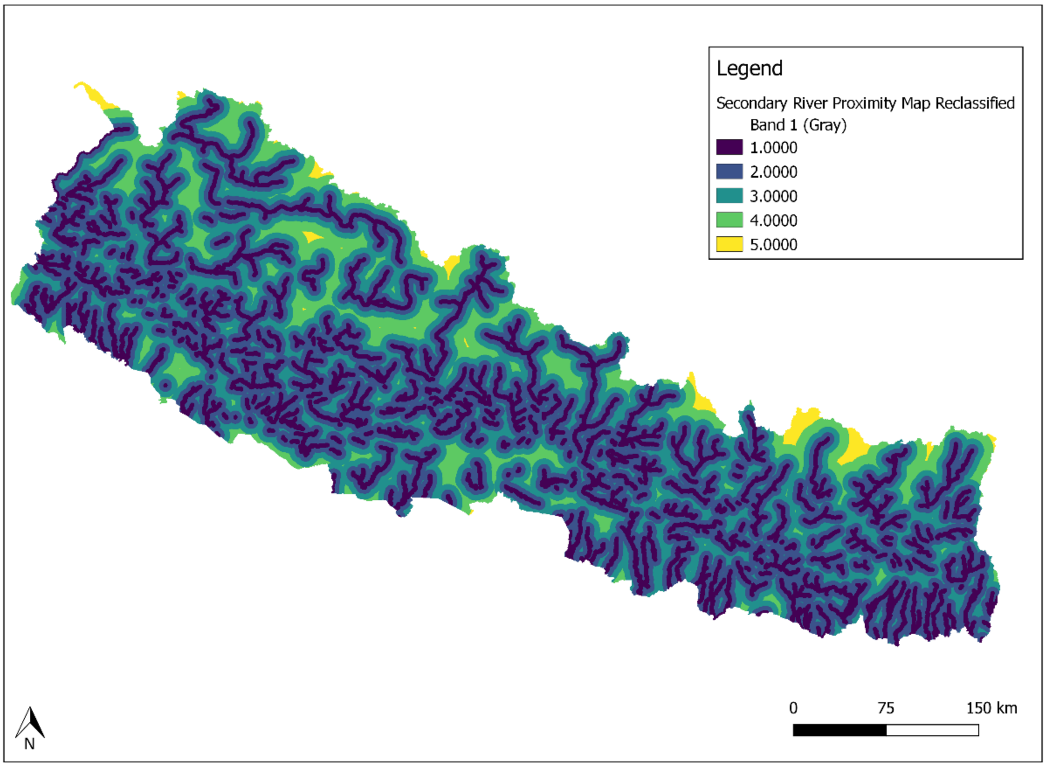

Figure 9.10: Reclassified Proximity Distribution of Secondary River Network of Nepal

Table 9.10: Reclassification Table (Secondary river)

Actual Values (meter)	Reclassified Values
< 1667.77	1
1667.77 – 5134.70	2
5134.70 – 9610.88	3
9610.88 – 17399.30	4
> 17399.30	5

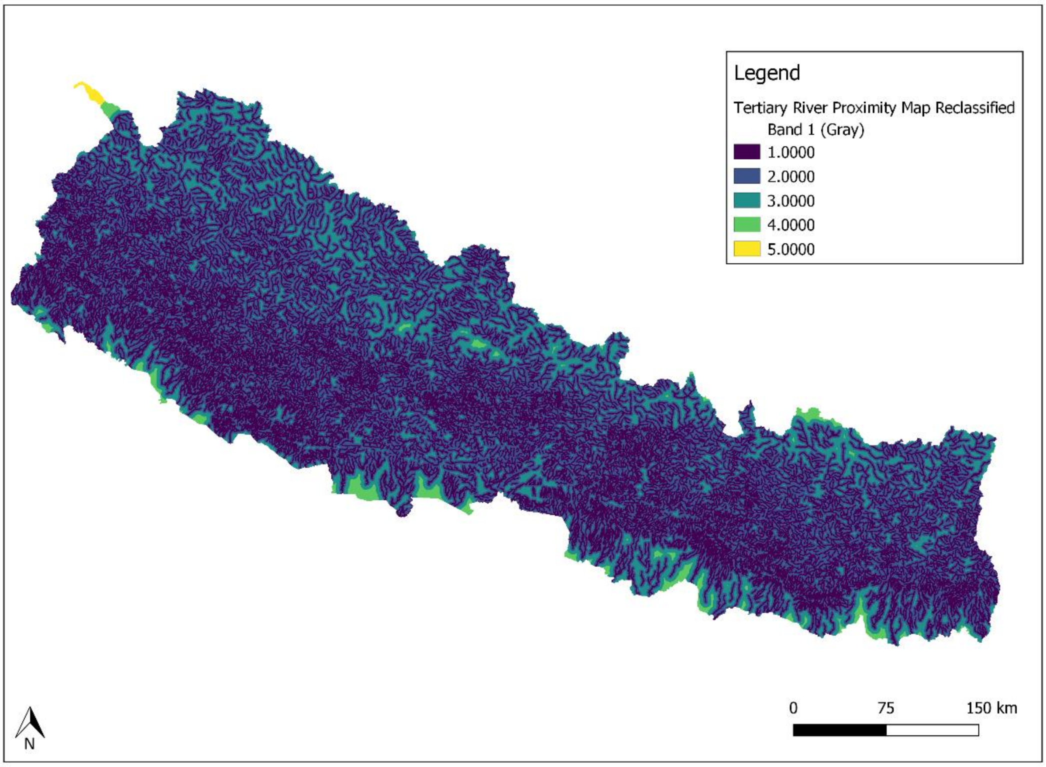

Figure 9.11: Reclassified Proximity Distribution of Tertiary River Network of Nepal

Table 9.11: Reclassification Table (Tertiary river)

Actual Values (meter)	Reclassified Values
< 469.24	1
469.24 – 1684.76	2
1684.76 – 4485.65	3
4485.65 – 16296.19	4
> 16296.19	5

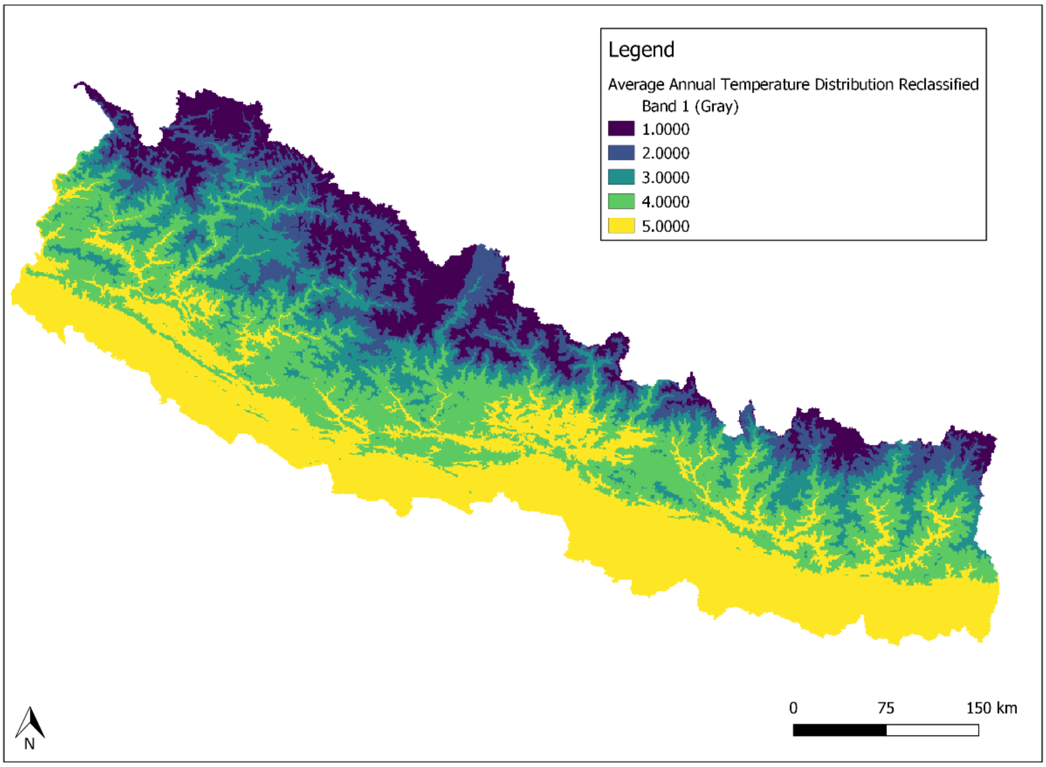

Figure 9.12: Reclassified Annualized Average Temperate Distribution of Nepal

Table 9.12 Reclassification Table (Temperature Map)

Actual Values	Reclassified Values
< -3.8	1
-3.8 – 4.721	2
4.721 – 13.410	3
13.410 – 20.502	4
> 20.502	5

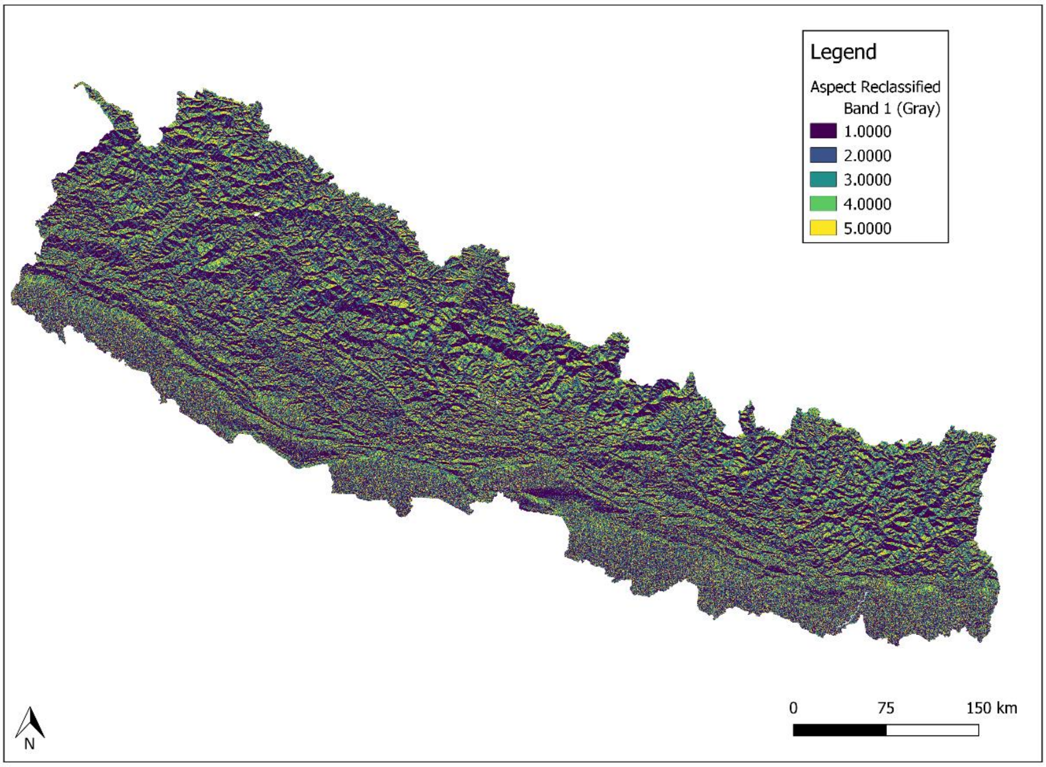

Figure 9.13: Reclassified Aspect Distribution Map of Nepal

Table 9.13 Reclassification Table (Aspect Map)

Actual Values (degrees)	Reclassified Values
South / flat (180-202.5, 157.5 – 180)	5
202.5 - 225, 135 – 157.5	4
225 - 247.5, 112.5 - 135	3
247.5 - 270, 90 - 112.5	2
270 - 360, 0-90	1

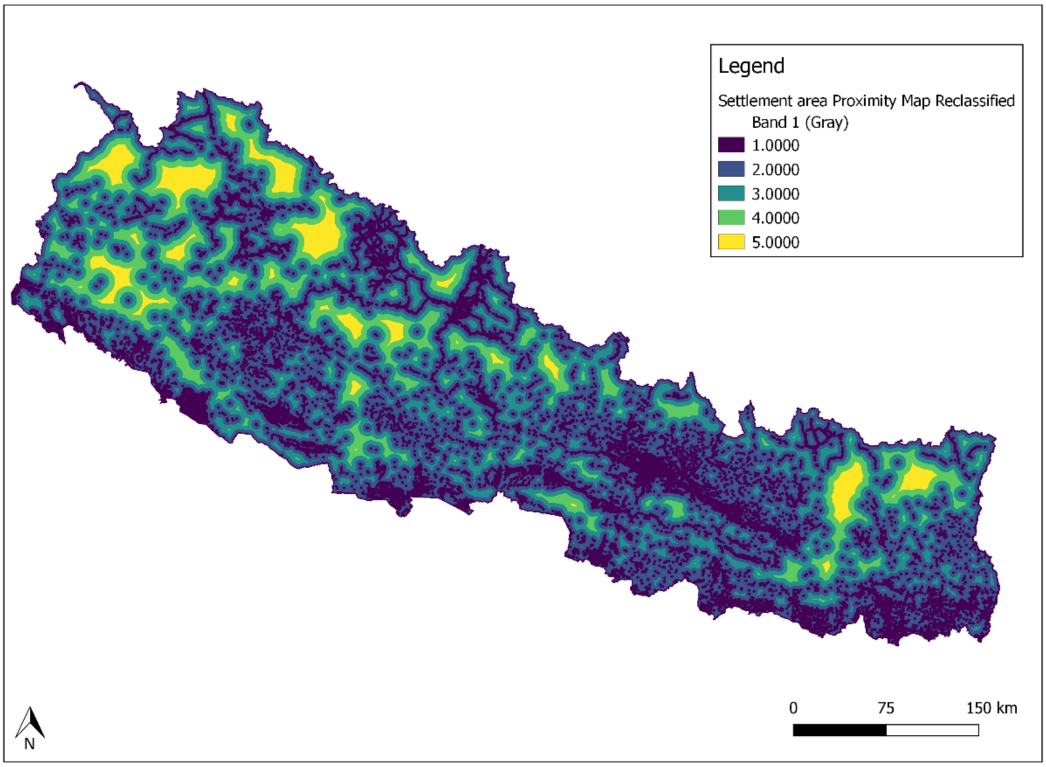

Figure 9.14: Reclassified Proximity Distribution of Settlement region of Nepal

Table 9.14 Reclassification Table (Settlement map)

Actual Values (meter)	Reclassified Values
< 1107.61	1
1107.61 – 3553.16	2
3553.16 – 6830.85	3
6830.85 – 11577.78	4
> 11577.78	5

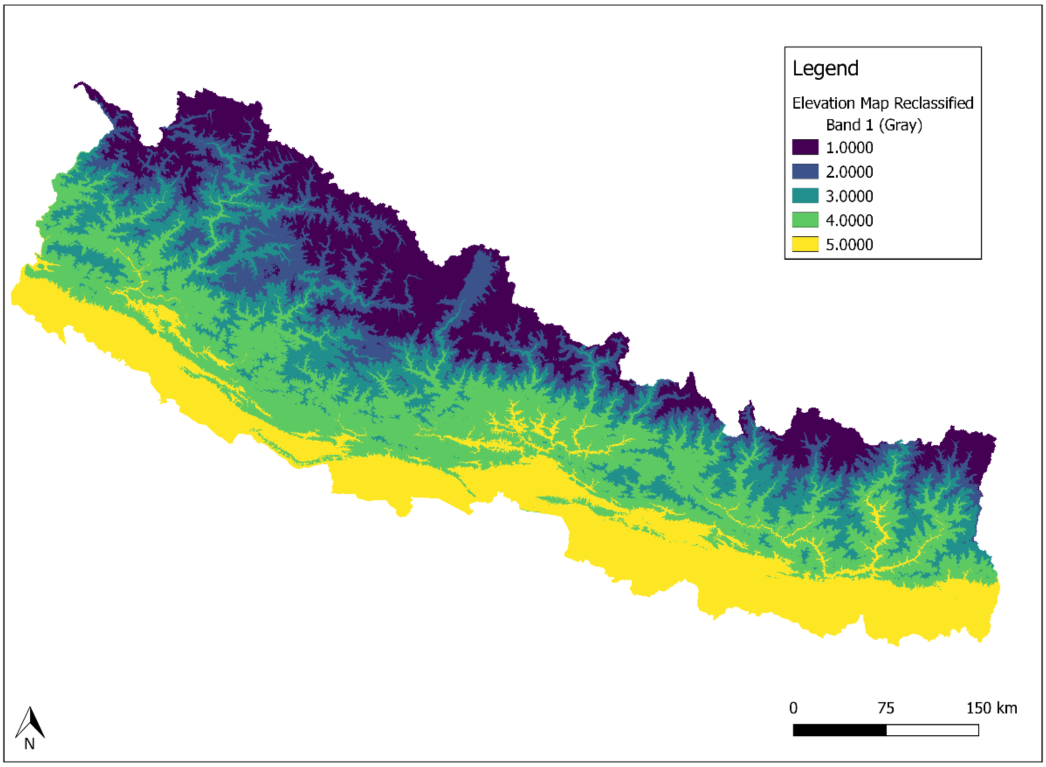

Figure 9.15: Reclassified Elevation Map of Nepal

Table 9.15 Reclassification Table (Elevation map)

Actual Values (meter)	Reclassified Values
< 554	5
554 – 1672.63	4
1672.63 – 2980.80	3
2980.80 – 4446.25	2
> 4446.25	1

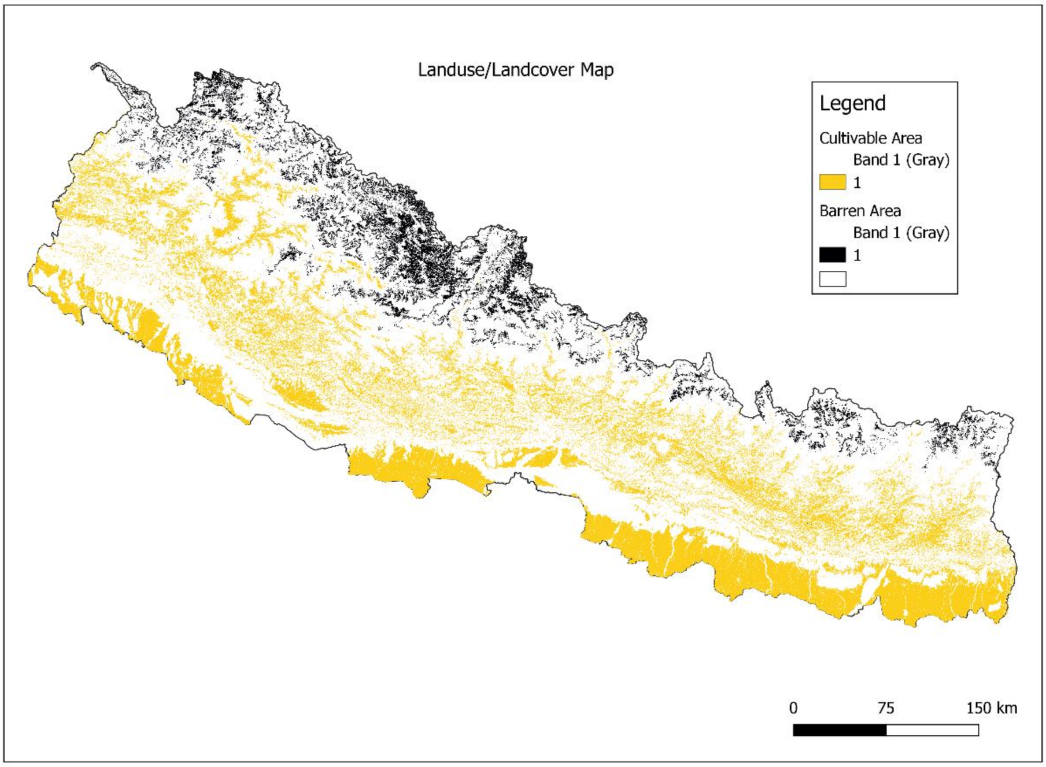

Figure 9.16: Barren and Cultivable Area cover of Nepal

Appendix-III: Regional Distribution of Site Suitability

Table 10.1: Distribution Of Suitable Area Across Provinces (by land area)

Province	Least Suitable (sq. km)	Marginally Suitable (sq. km)	Moderately Suitable (sq. km)	Highly Suitable (sq. km)	Most Suitable (sq. km)	Total Area (sq. km)
1	18048.52	1023.87	1844.01	4388.63	696.67	26001.7
2	3481.49	0	0	343.66	5711.58	9536.73
3	15157.18	720.82	888.66	2629.79	844.86	20241.31
4	16440.97	2030.09	1448.07	1221.96	779.2	21920.29
5	12482.1	153.74	352.2	1331.63	4945.37	19265.04
6	22734.86	4083.47	1432.45	1524.77	826.39	30601.94
7	15374.41	423.17	680.76	1426.85	2153.98	20059.17

Table 10.2: Distribution Of Suitable Area Across Provinces (by percentage)

SN.	Suitability (%)	Province No.						
		1	2	3	4	5	6	7
1	Least Suitable	69.41	36.51	74.88	75.00	64.79	74.29	76.65
2	Marginally Suitable	3.94	0.00	3.56	9.26	0.80	13.34	2.11
3	Moderately Suitable	7.09	0.00	4.39	6.61	1.83	4.68	3.39
4	Highly Suitable	16.88	3.60	12.99	5.57	6.91	4.98	7.11
5	Most Suitable	2.68	59.89	4.17	3.55	25.67	2.70	10.74

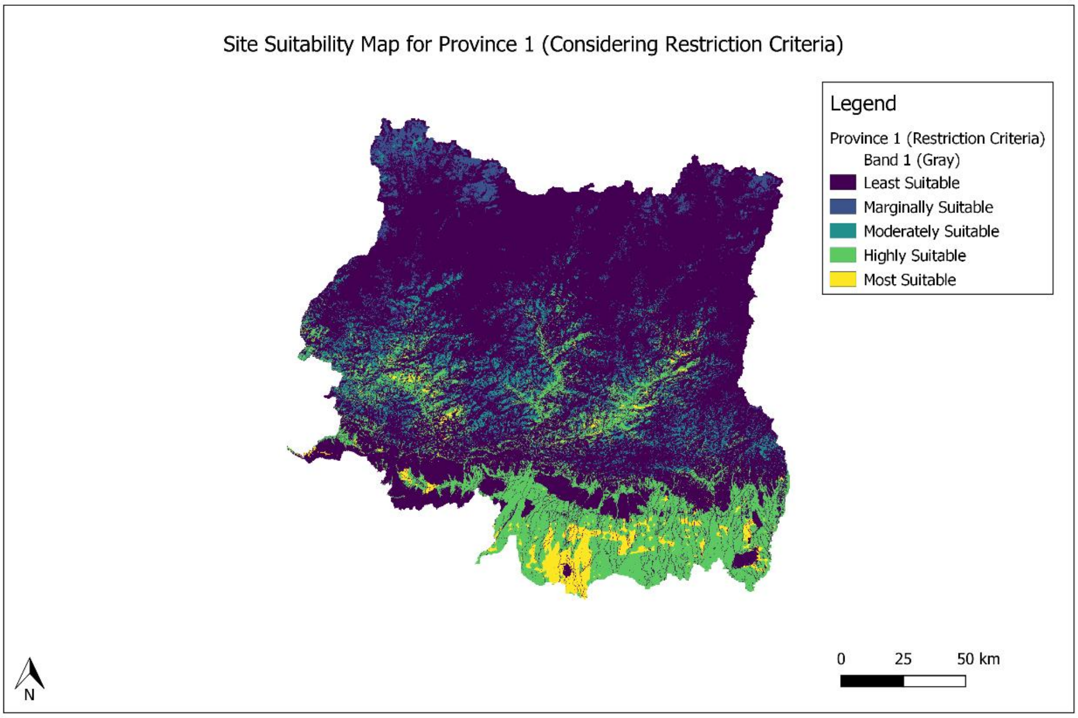

Figure 10.1: Solar PV Site Suitability for Province-1

Table 10.3: Zonal Statistics of Province-1

Sn.	Suitability	Area Coverage (sq. km)	Percentage Coverage (%)
1	Least Suitable	18048.52	69.41
2	Marginally Suitable	1023.87	3.94
3	Moderately Suitable	1844.01	7.09
4	Highly Suitable	4388.63	16.88
5	Most Suitable	696.67	2.68

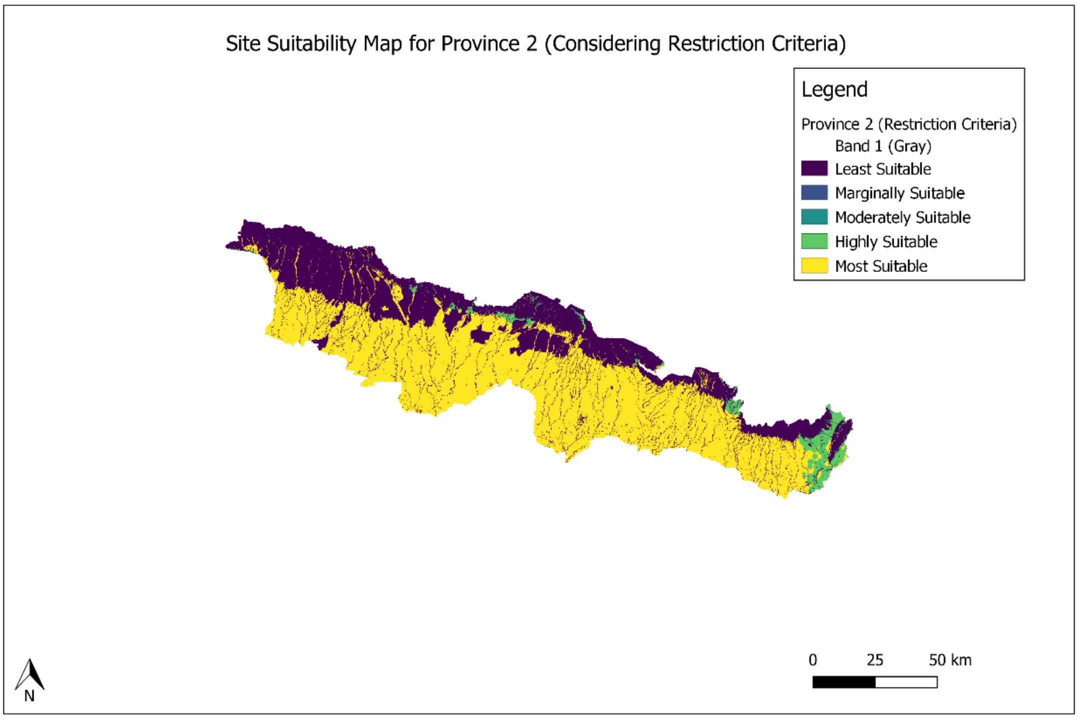

Figure 10.2: Solar PV Site Suitability for Province-2

Table 10.4: Zonal Statistics of Province-2

Sn.	Suitability	Area Coverage (sq. km)	Percentage Coverage
1	Least Suitable	3481.49	36.51
2	Marginally Suitable	0.00	0.00
3	Moderately Suitable	0.00	0.00
4	Highly Suitable	343.66	3.60
5	Most Suitable	5711.58	59.89

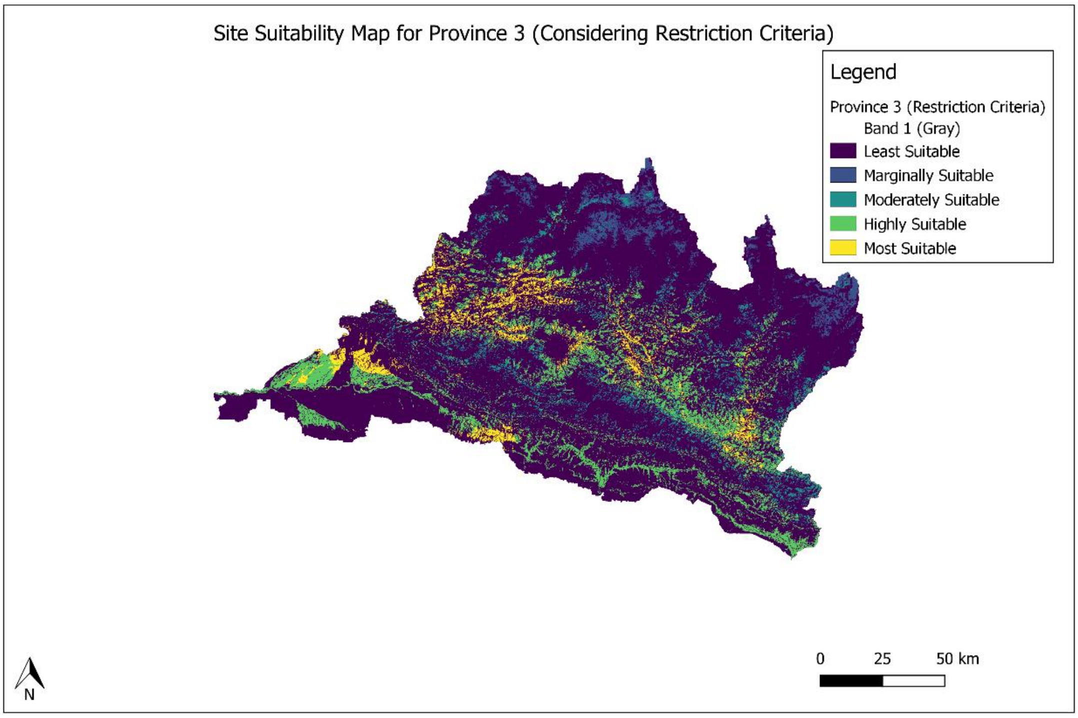

Figure 10.3: Solar PV Site Suitability for Province-3

Table 10.5: Zonal Statistics of Province-3

Sn.	Suitability	Area Coverage (sq. km)	Percentage Coverage
1	Least Suitable	15157.18	74.88
2	Marginally Suitable	720.82	3.56
3	Moderately Suitable	888.66	4.39
4	Highly Suitable	2629.79	12.99
5	Most Suitable	844.86	4.17

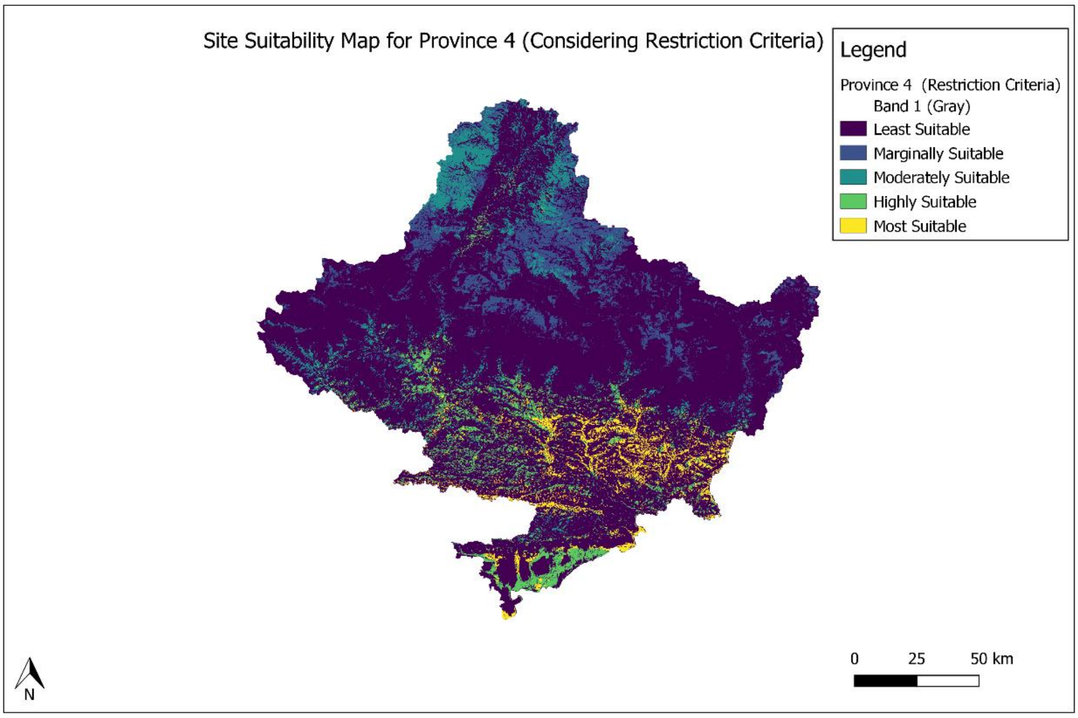

Figure 10.4: Solar PV Site Suitability for Province-4

Table 10.6: Zonal Statistics of Province-4

Sn.	Suitability	Area Coverage (sq. km)	Percentage Coverage
1	Least Suitable	16440.97	75.00
2	Marginally Suitable	2030.09	9.26
3	Moderately Suitable	1448.07	6.61
4	Highly Suitable	1221.96	5.57
5	Most Suitable	779.20	3.55

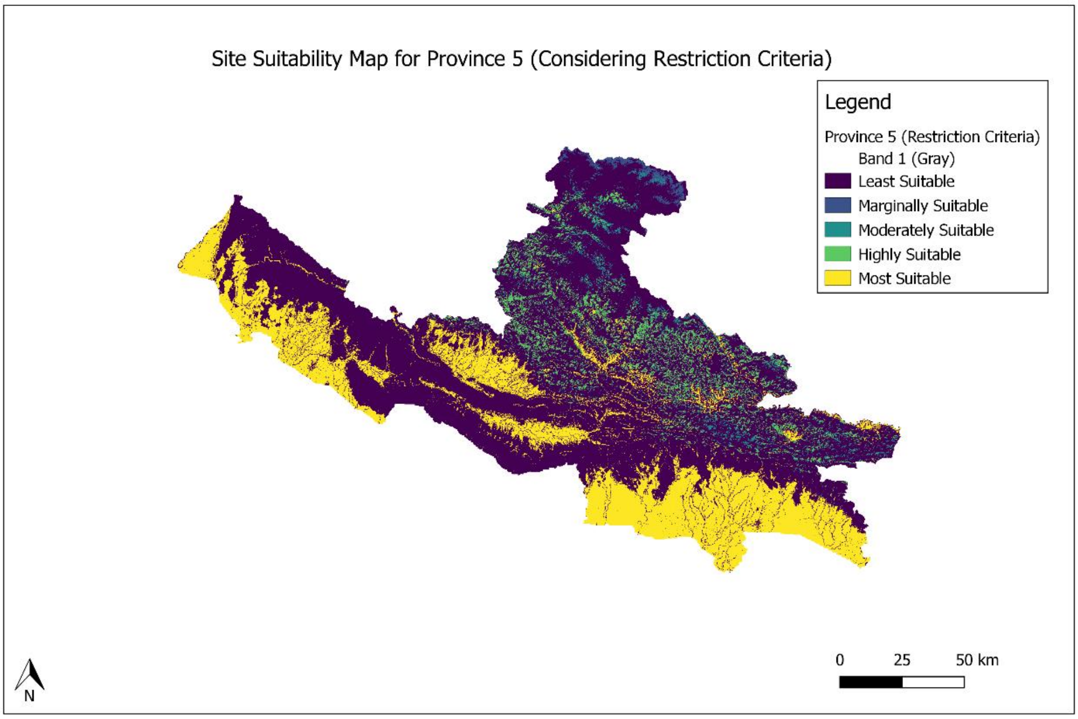

Figure 10.5: Solar PV Site Suitability for Province-5

Table 10.7: Zonal Statistics of Province-5

Sn.	Suitability	Area Coverage (sq. km)	Percentage Coverage
1	Least Suitable	12482.10	64.79
2	Marginally Suitable	153.74	0.80
3	Moderately Suitable	352.20	1.83
4	Highly Suitable	1331.63	6.91
5	Most Suitable	4945.37	25.67

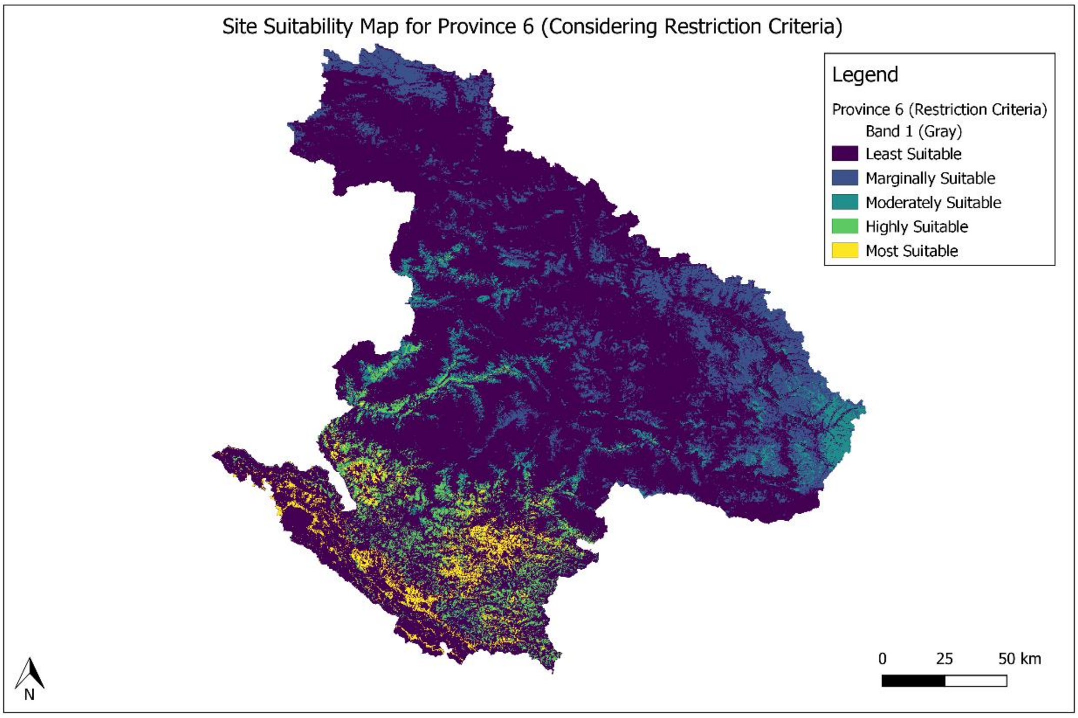

Figure 10.6: Solar PV Site Suitability for Province-6

Table 10.8: Zonal Statistics of Province-6

Sn.	Suitability	Area Coverage (sq. km)	Percentage Coverage
1	Least Suitable	22734.86	74.29
2	Marginally Suitable	4083.47	13.34
3	Moderately Suitable	1432.45	4.68
4	Highly Suitable	1524.77	4.98
5	Most Suitable	826.39	2.70

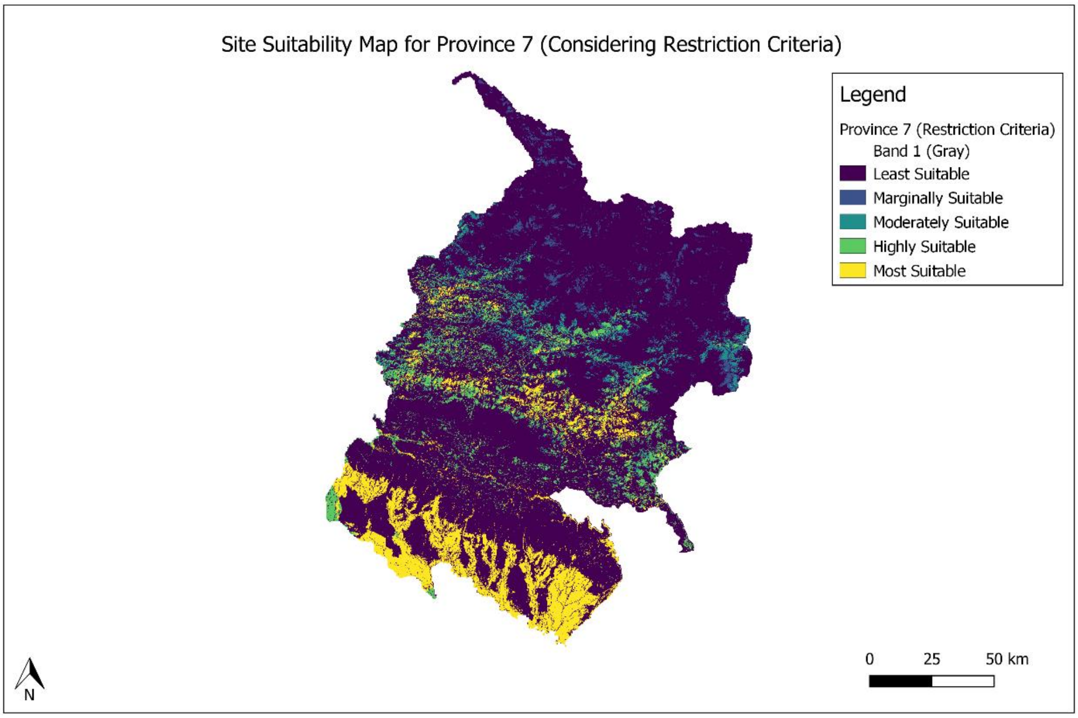

Figure 10.7: Solar PV Site Suitability for Province-7

Table 10.9: Zonal Statistics of Province-7

Sn.	Suitability	Area Coverage (sq. km)	Percentage Coverage
1	Least Suitable	15374.41	76.65
2	Marginally Suitable	423.17	2.11
3	Moderately Suitable	680.76	3.39
4	Highly Suitable	1426.85	7.11
5	Most Suitable	2153.98	10.74

A study on site identification for Utility Scale Solar PV Energy Generation in Nepal

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